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JUDUL : **CORROSION MANAGEMENT OF STEEL REINFORCED CONCRETE**

SESI PENGAJIAN : 2005 / 2006

Saya **CHEW WE-SEN**

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CORROSION MANAGEMENT OF STEEL REINFORCED CONCRETE

CHEW WE-SEN

A project report submitted in partial fulfillment of the requirements for the award of the Degree of Master of Science (Construction Management)

Faculty of Civil Engineering
Universiti Teknologi Malaysia

APRIL, 2006

I declare that this thesis entitled "Corrosion Management of Steel Reinforced Concrete" is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature	: ____________________
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DATE	: APRIL 2006

TO MY BELOVED MOTHER , FATHER AND SISTERS

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ABSTRACT

Structural failures are closely linked with the corrosion of steel bar in reinforced concrete. Repair or maintenance works on corroded structures are usually costly. Corrosion is actually a slow process and can be detected for further repair before causing any damage. Failure to do so would only cause expensive economical as well as physical damage to the structure itself. Corrosion management includes activities performed to mitigate corrosion, to repair corrosion-induced damage and to replace the structures that are badly corroded. The objectives of this study are to study the corrosion management program, to identify the methods of corrosion prevention, to evaluate the cost-benefit ratio of corrosion management and to identify the problems in the management of corrosion. The study was carried out by conducting literature reviews, questionnaires and interviews. The data collected through questionnaires were then analyzed using average mean index. The outcome of the study indicates that awareness of practicing professional is relatively low regarding issues on corrosion management. The potential of cost saving through implementation of proper management program can be surprisingly high

ABSTRAK

Kegagalan struktur pada kebiasaannya berkait rapat dengan masalah pengaratan besi tetulang dalam konkrit. Kerja penyelenggaraan atas struktur yang berkarat pada kebiasaannya akan menyebabkan kos yang tinggi. Pengaratan adalah prosess yang perlahan dan keadaannya boleh dibaiki. Kegagalan untuk memperbaiki masalah pengaratan pada fasa awal hanya akan menelan kos yang lebih tinggi. Program pengurusan pengaratan termasuk aktiviti-aktiviti yang dilaksanakan untuk memberhentikan pengaratan, membaiki pulih struktur yang berkarat dan juga mengganti anggota struktur yang terkarat. Kajian ini dijalankan untuk menentukan tatacara pengurusan masalah pengaratan yang berpotensi untuk menjimatkan kos. Untuk mencapai matlamat kajian ini, soal selidik, temubual serta kajian kes telah dilaksanakan. Keputusan daripada kajian ini didapati bahawa tahap kesedaran para professional terhadap masalah pengaratan masih rendah. Masalah ini perlu diatasi supaya pelaburan ke atas struktur adalah lebih effisien. Juga didapati, jumlah wang yang berpontensi boleh dijimatkan adalah tinggi sekiranya adanya system pengurusan yang baik terhadap masalah pengaratan.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF APPENDIX

CHAPTER I

INTRODUCTION

1.1 Introduction

Corrosion is a natural process. The problem started as soon as human started digging the ores. It terrorized industries that have the application of steel ranging from chemical plant, power plant and agricultural sector. However, corrosion that takes place in construction industry is the most critically acclaimed as it involves the lives of human being living under these structures.

Corrosion of rebars in concrete structure is a major problem in the construction industry. Corrosion is generally caused by chloride attack and carbonation which are acidic reaction. Concrete which contains microscopic pores with high concentration of soluble calcium, sodium and potassium oxides are highly alkaline. Ironically, alkalinity is the opposite of acidic. Under high alkalinity condition in concrete, a layer of passive protection would form on the steel surface. A passive layer is a dense, impenetrable film, which if fully established and maintained, prevent further corrosion of steel.

However, as mentioned above, two processes can break down the passivating environment in concrete, one is chloride attack while the other one is carbonation. Therefore, the passive layer is not always maintained.

It was reported that corrosion of metal cost the U.S economy some near $300 billion per year as published by National Association of Corrosion Engineer (NACE). As a general statement, the cost of combating corrosion would keep on growing as long as the country has the capacity to develop. Therefore, it shows that a proper system is very much in need to manage to rising problem of corrosion.

1.2 Problem statement

Concrete is strong in compression but weak in tension. Based on this statement, other material has been introduced to the manufacturing of concrete in hoping to increase the tensile strength of it. Thus, the term of reinforced concrete has been created. Reinforced concrete can be defined as introduction of steel in concrete structure purely for the purpose of strengthening its tensile properties.

Reinforced concrete is a very versatile structure as it can be moulded into variety of shapes. Therefore, application of reinforced concrete is usually very wide in the construction industry. Ranging from substructure to super structure, from beams to columns, from slabs to walls, reinforced concrete can be found in almost every member of the structure.

However, one common problem face by engineers around the globe is that reinforced concrete is an aging material. In other word, the steel will corrodes as time goes by. The severe environment condition in tropical region as well as the process of deicing of saltwater in seasonal countries has led to shorter lifetime of a structure. Right after planting of metal into concrete, nature sets the reversing process.

Of all that, it has prompted one common interest, to study, understand and tackle the problems of corrosion. Realizing the damage and potential danger caused by corrosion, researchers have taken the initiative to identify the mechanism of corrosion and thus introduce methods of curing for it. The methods that are commonly practiced will be further discussed in this study.

As the saying of "prevention is better than cure" goes by, it is wise to design and construct the structure accordingly to avoid any inconvenience.

Corrosion is actually a slow process and can be detected for further repair before causing any damage. Failure to do so would only cause expensive economical as well as physical damage to the structure itself. For that, overlooking the maintenance aspect of a structure could prove to be a costly error.

1.3 Objectives

Engineered structures are built to serve with a purpose. However, all members of a structure undergoes the process of aging. For instance, the most significant aging process is the corrosion of steel in reinforced concrete member.

Corrosion management includes all activities throughout the service life of the structure that are performed to mitigate corrosion, to repair corrosion-induced damage and to replace the structures that are badly corroded. All these activities are governed by large sum of money and are characterized by annual cost. These factors had triggered the need for a proper and systematic ways of conducting corrosion management for reinforced concrete structures ensure maximum profit. In this study, the main objectives are:

1. To study the corrosion management programs.
2. To identify the methods of corrosion prevention.

3. To evaluate the cost-benefit ratio of the management program.
4. To identify the problems in corrosion management.

1.4 Scope of studies

Among the methods that will be carried out to determine the current trend in Malaysia are as follow:

a. Interviews with local contractors, consultants and developers.
b. Survey, in the form of questionnaire to be handed out to local contractors, consultants and developers.
c. Internet research.
d. Application of cost analysis to determine the cost-benefit ratio for corrosion prevention program.
e. Reference of previous studies.

CHAPTER II

LITERATURE REVIEW

2.1 Electrochemical Theory of Corrosion

Concrete is understood of having very high compression strength but weak in tension. Therefore, usage of steel bar is introduced to the construction of concrete to strengthen tensile strength to tackle the occurrence of cracking due to loading on top of the structure. However, one major problem of applying steel bar in concrete is that it is prone to corrosion.

The phenomenon of corrosion that leads to the breaking down of the passive layer on steel surface is being termed as electro-chemical reaction [1].

When steel is brought into an aquaes environment, the iron goes into the solution as ferrous ion :

Anode : $Fe \longrightarrow Fe^{2+} + 2e^{-}$

There is therefore a difference between the electrode potential. To achieve equilibrium of neutrality, the two electron must be consumed. Therefore, the electron will be transported over to cathode electrode through the solution (electrolyte). Transportation of the electrons causes an electrical current to flow in the electrolyte. Over at the cathodic region, a cathodic reaction of :

Cathode : $H_2O + ?\ O_2 + 2e^- \longrightarrow 2OH^-$

Both the anodic and cathodic reaction are only the first step in the process of creating rust. The hydroxyl ions (OH^-) created in the cathode would then be transported back to anode once again and form a reaction of :

Anode : $Fe^{2+} + 2OH^- \longrightarrow Fe(OH)_2$

to create ferrous hydroxide. Figure 2.1 illustrate the reaction at the anode and cathode of a reinforcement.

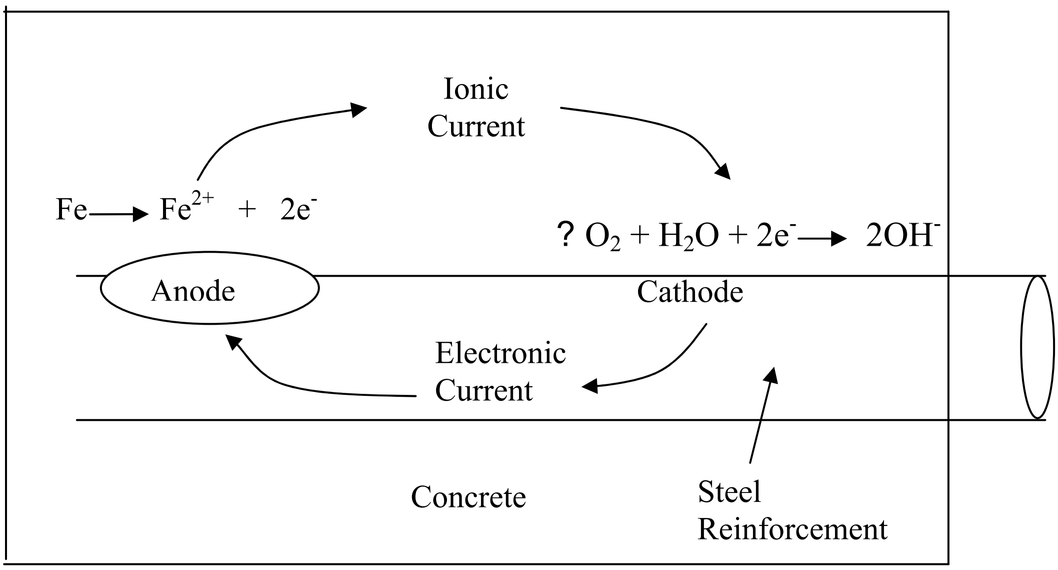

Figure 2.1 The anodic and cathodic reactions

With the presence of O_2(oxygen) and H_2O(water), ferrous hydroxide would generate a reaction of :

$4Fe(OH)_2 + O_2 + 2H_2O \longrightarrow 4Fe(OH)_3$

to produce ferric hydroxide. Eventually, the ferric hydroxide would react :

$$2Fe(OH)_3 \longrightarrow Fe_2O_3.H_2O + H_2O$$

to form hydrated ferric hydroxide which is rust.

The same scenario can be applied on reinforced concrete with steel acting as cathode and anode while pore water as electrolyte. Figure 2.2 showing the reaction of corrosion on a reinforcement bar.

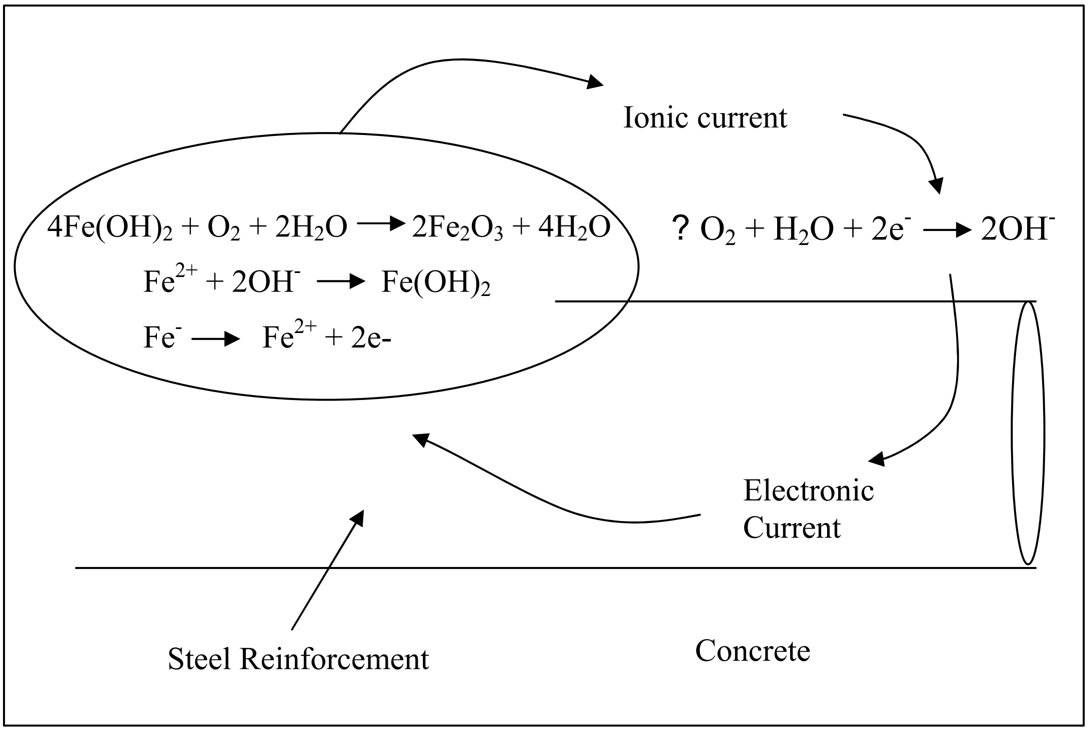

Figure 2.2 The corrosion reactions on steel

2.2 Mechanism of Corrosion

The main causes of corrosion on rebars are chloride attack and carbonation. Typical chloride attack and carbonation do not attack or damage the concrete cover like those nominal deterioration processes due to chemical attack. Instead, the aggressive chemical passes through the pores in concrete and directly corrodes the steel.

Acid or other aggressive chemical substances are more likely to destroy and damage the cover of concrete before posing any threats on the steel [3]. However, carbon dioxide and chloride ion are capable of penetrating through concrete without damaging it.

Corrosion caused by chloride ion is being termed as chloride attack while carbonation meaning attack by carbon dioxide. This chapter would focus on the mechanism of both processes:

2.2.1 Chloride Attack

Presence of chloride ion in concrete are likely due to :

a. Deliberate addition of chloride set accelerator.
b. Use of seawater in the mix.
c. Contaminated aggregates which are unwashed or inadequately washed.

Chloride can also penetrate into concrete from outside due to:

a. Splash of seawater.
b. Deicing of salts.
c. Application of chemical. (chemical storage tank)

Inductions of chloride ion in concrete are believed to be through the process of suction, especially when the surface is dry [4]. For the case of marine structures, salt water are absorbed by dry concrete. It is understood that chloride ions are not consumed during the process of depassivation, but is somewhat play the role of catalyst to speed up the process of breaking down the passive layer thus allowing corrosion to proceed quickly.

This is illustrated in Figure 2.3. Chlorides are hard to eliminate making them hard to cure.

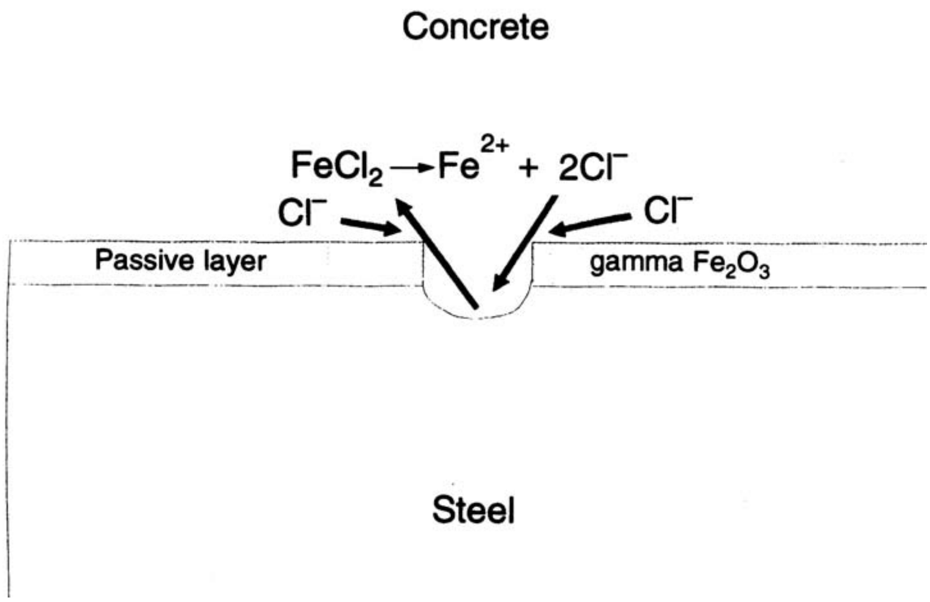

Figure 2.3 The breakdown of the passive layer and recycling chlorides [1].

A few chloride ions are not capable of doing any damage to the passive layer, but there is a chloride threshold measured by the chloride / hydroxyl ratio. Hausmann (1967) suggested that when the ratio reaches or exceed 0.6, then corrosion will occurred [1]. This is equivalent to a concentration of 0.4% chloride by weight of cement if chlorides are cast into concrete and 0.2% if they are diffused in. However, these thresholds are only approximations because:

1. The value of pH of concrete depends on the type of cement and the concrete mix. Therefore, a tiny pH change represents a massive change in hydroxyl ions (OH^-) concentration and the threshold moves radically with pH.
2. Chlorides are bounded chemically by aluminates in the concrete and physically by the adsorption on the pore walls. This removes them from the corrosion reaction. Sulphate resisting cements have low aluminate (C_3A) content which leads to more rapid diffusion and lower chloride threshold.
3. For a very dry concrete, corrosion might not occur even at very high chlorides ions concentration as the water is missing from the corrosion reaction.

4. For an enclosed concrete, corrosion might not occur even at very high chloride ions concentration if there is no oxygen to trigger the corrosion reaction.
5. Corrosion might not occur in a fully saturated environment due to oxygen starvation.

Therefore corrosion can be observed at a threshold level of 0.2% chloride by weight of cement if the quality is poor and there are water and oxygen available. Under different circumstances no corrosion may be seen at 1.0% chloride or more if oxygen and water are excluded.

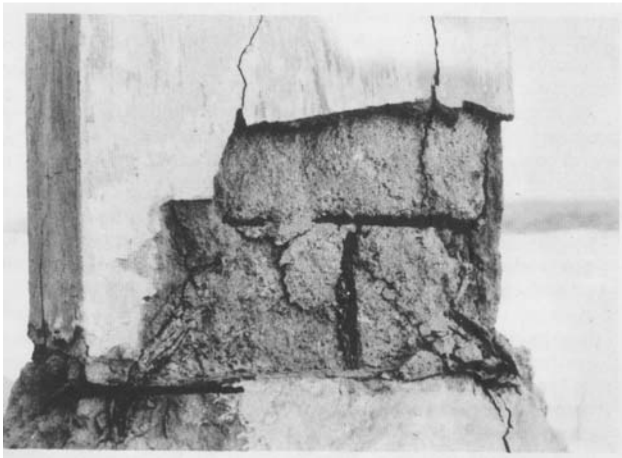

Figure 2.4 Chloride attack and spalling of concrete [2].

2.2.2 Carbonation

Carbonation meaning penetration and hence interaction of atmospheric carbon dioxide (CO_2) with the alkaline hydroxide in the concrete. Dissolution of carbon dioxide in water forms an acid that neutralizes the alkalis in pore water forming calcium carbonate.

$$CO_2 + H_2O \longrightarrow H_2CO_3 \text{ (carbonic acid)}$$

$$H_2CO_3 + Ca(OH)_2 \longrightarrow CaCO_3 + 2H_2O$$

Continuous carbonation will results in the reduction of the pH of the pore water to values below 9.5 once the availability of local calcium hydroxide finishes. Theoretically, the passive film disappears at a pH of about 8 and if the value falls below 7, catastrophic corrosion can occur.

The rate of penetration depends much on the porosity and permeability of the concrete which is influenced by water-cement ratio and method of casting. Therefore, the risk of carbonation on a well compacted and cured structure with low water but high cement content is at its minimal. Sufficient thickness of the cover should be applied to ensure the lifetime of the structure can actually outlast the penetration rate before carbonation reaches the reinforcement. To simplify that statement, it can be defined as the carbonation rate is inversely proportionate to the thickness. It can be explained by mathematical equation of:

$$X = D \sqrt{t}$$

Where x is distance, t is time and Do is the diffusion constant. In other word, carbonation is the function of cover thickness. Therefore, good cover is essential to resist carbonation.

2.3 Corrosion damage

Fears of corrosion damage in other industries are mainly over the problem of loss of metal but otherwise for the case of reinforced concrete. Structural failure due to corrosion for construction industry is very rare [13]. As a matter of fact, the fear of corrosion in reinforced concrete is the growth of oxide that would eventually lead to cracking and spalling of the concrete cover.

The formation of a dense oxide at high temperature has twice the volume of the steel consumed. Under aqueous condition, the excess oxide would be carried away from the steel surface and deposits on open surfaces within the structure. However for the case of reinforced concrete, the water pores are static meaning no transportation mechanism for the excess oxides hence it will be accumulated at the metal / oxide interface. The oxides are very porous and takes up a very large volume as illustrated in Figure 2.5. This would separate the concrete from the steel and the process of cracking and spalling of the structure would take place.

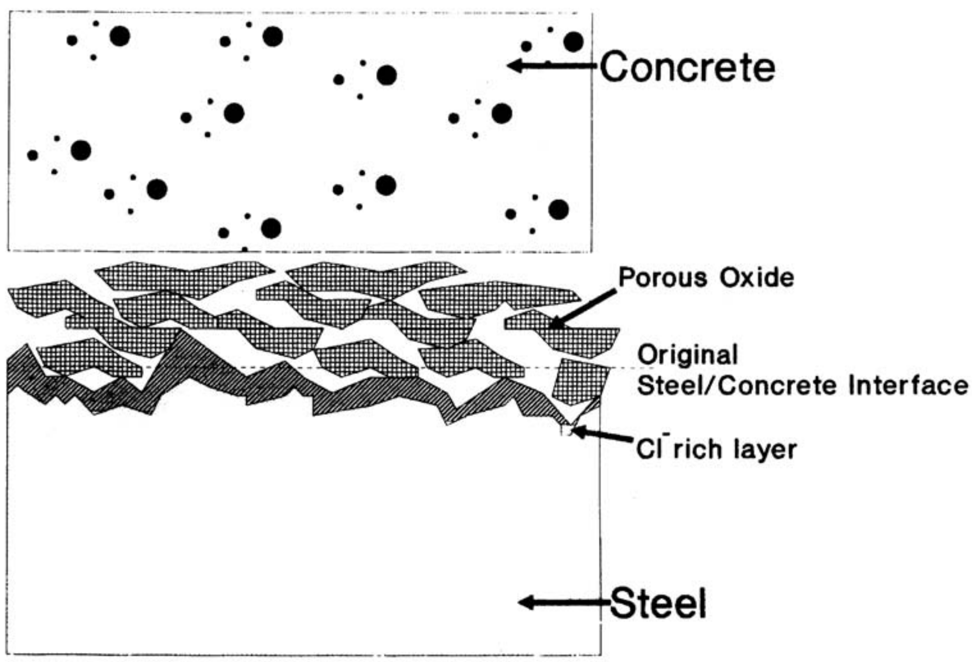

Figure 2.5 Rust growth forcing steel and concrete apart.

2.4 Types of reinforcement corrosion

As mentioned earlier, the main causes that lead to corrosion are carbonation and chloride attack. However, the availability of moisture, oxygen and a low-resistivity electrical path through the concrete are required for the process to be activated. The types of corrosion depend very much on all of these factors.

2.4.1 General Corrosion

When chloride or carbonation process reaches the surface of the reinforcement bar, the protective oxide film on the bar will be progressively destroyed. Availability of oxygen under such condition will trigger the corrosion cell surrounding the area thus causing corrosion to take place uniformly over the whole of the steel surface. The product from this corrosion are mainly iron oxides in which have a larger volume than steel that would cause an increase of size thus induced cracking and eventually spalling of the structure.

2.4.2 Pitting corrosion

Also known as “localized corrosion” as it takes place over a more specific area. This corrosion occurs when build-up of chloride ion at an isolated location leads to localized breakdown of the passive protective film at the spot. This will eventually leads to the creation of a pit on that spot as shown in Figure 2.6. The product of this corrosion is in the form of soluble ferric chloride which will disperse into concrete. Therefore, pitting corrosion require some time before showing any visual sign of structural damage.

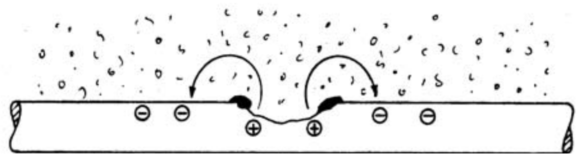

Figure 2.6 Pitting corrosion in a freely corroding bar [1]

2.4.3 Bacterial corrosion

Microbiologically induced corrosion basically occurs only in anaerobic conditions where oxygen is totally excluded. Bacteria under these condition convert sulphur to sulphate acid which will attack the steel surface and create a series of iron sulphide that enable corrosion reaction to proceed even in the absence of oxygen.

2.4.4 Concentration cells

A potential difference between the steel in each different area is created when the reinforcement passes through regions of concrete containing varying amounts of soluble ion. The potential difference allows corrosion to be initiated at the anodic site.

2.4.5 Differential-oxygen cells

The formations of these cells arise due to the differences in oxygen supply to different parts of the reinforcement network. In other word, these cells are formed when there is a variation in the rate of arrival of dissolved oxygen to different parts of a metallic surface. Process of the corrosion is as shown in Figure 2.7. Common area suffering from this corrosion is the discharge area for a water storage tank where that particular area has greater access to oxygen. Under these conditions, the oxygen starved regions becomes anodic and undergo corrosion attack.

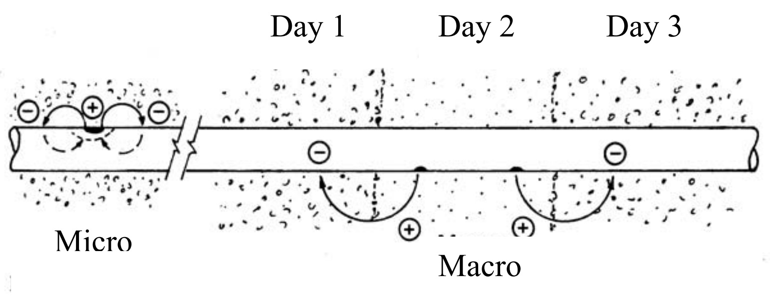

Figure 2.7 Concentration and differential-aeration cells in concrete [1].

2.4.6 Dissimilar metal corrosion

When steel is in contact with different metal or alloy which is lower in the galvanic series, the less active metal in the galvanic series will undergo corrosion in the presence of a moisture path acting as electrolyte. Table 2.1 shows the order of metal in galvanic series.

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Table 2.1 Order of metal in galvanic series

1. Zinc	7. Lead
2. Aluminum	8. Brass
3. Steel	9. Copper
4. Iron	10. Bronze
5. Nickel	11. Stainless Steel
6. Tin	12. Gold

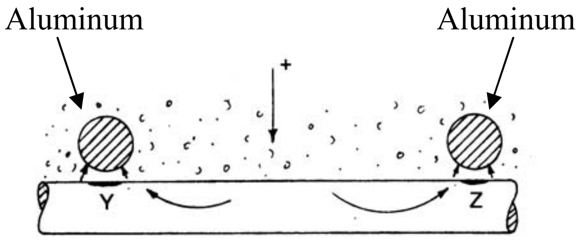

Figure 2.8 Dissimilar metal corrosion [1].

One common situation is the use of aluminum that was cast into reinforced concrete as an electrical conduit. As the aluminum is higher in the galvanic series, it tends to corrode while the surface of the reinforcement remains clean. Figure 2.8 above illustrate the process of dissimilar corrosion. However, the white oxide grown around the aluminum surface will cause tensile forces which will eventually initiate cracking at the surrounding concrete. This corrosion is also known as dissimilar metal corrosion.

2.5 Methods of Prevention

2.5.1 Designing for Durability

The most effective and efficient way of preventing corrosion begins from the design phase. Design phase includes structural design as well as concrete design which refer to how the concrete is prepared, placed, compacted and cured.

Before implementing any design method as a mean to prevent corrosion, engineers are required to understand the function of the structure and the conditions of aggressiveness the structure would encounter. Among the elements that must not be overlooked are humidity of the environment, its variability in time and place, the presence of chlorides and oxygen and the temperature. Generally speaking, the environment is not aggressive if it is sufficiently dry whereby the humidity (expressed in percentage) is lower than 70% to 60%. However, one must be aware that exposure to marine atmosphere are aggressive regardless of the humidity or level of contact with seawater.

The environment is considered as the sum of chemical and physical actions to which the concrete is exposed and that result in effects on the concrete or the reinforcement or embedded metal that are not considered as loads in structural design as defined in the European Standard EN 206. However, for the purpose of this study, we would only concentrate on chemical attack.

2.5.1.1 Concrete Quality

The resistance of a structure against corrosion depends much on a wide range of properties that are generally taken together in the term “quality of concrete”, which includes it composition and the care with which it is executed. Major items that contribute to the properties of the concrete are:

a. water-cement ratio (w/c)
b. cement content.
c. cement type.
d. mixing, placing, compaction and curing.

All the above mentioned items play a significant role in producing quality concrete to curb corrosion. Under certain circumstances, one item appears to have more significant effect on quality of concrete. Table 2.2 below indicates the recommended choice of limiting values of concrete composition and properties in relation to exposure classes according to EN 206.

Table 2.2 Recommended choice of limiting values of concrete composition in relation to exposure classes according to EN 206 [9].

Exposure class		Maximum w/c	Minimum Strength	Minimum cement content (km/m?)
Carbonation-induced corrosion	XC1 XC2 XC3 XC4	0.65 0.60 0.55 0.50	C20/15 C25/30 C30/37 C30/37	260 280 280 300
Chloride-induced corrosion (seawater)	XS1 XS2 XS3	0.50 0.45 0.45	C30/37 C35/45 C35/45	300 320 340
Chloride induced corrosion Cl- other than seawater	XD1 XD2 XD3	0.55 0.55 0.45	C30/37 C30/37 C35/45	300 320 320

2.5.1.2 Cover Thickness

It is understood that the function of cover is to protect the reinforcement from exposure to corrosive environment. Therefore, the concrete cover of reinforcement steels and stirrups must at no point be less than the values give in Table 2.3.

Table 2.3 Concrete cover thickness in relation to diameter of rod.

Diameter of Rod, mm	Concrete Cover, mm
≤ 12	10
14	
16	15
18	
20	
22	20
25	
28	25
>28	30

In some special cases, the concrete cover must be increased in order to provide maximum protection. For example, when the maximum size of the ballast is in excess of 32 mm, when concrete is in constant contact with water, and for washed and sandblasted areas. However, under certain circumstances, increasing concrete cover alone is not sufficient to curb corrosion activity and other protective measures such as external protecting layers should also be considered. Table 2.4 indicates minimum thickness of concrete cover depending on environmental condition.

Table 2.4 Minimum thickness of concrete cover depending on environmental condition [9].

Environmental Condition	Concrete Grade			
	Bn 150		> Bn 250	
	General	Loadbearing section	General	Loadbearing section
✍ Building component in enclosed area. ✍ Building component which remain constantly under water or kept permanently dry. ✍ Roof which are covered by waterproof skin, for the side on which the skin is positioned.	20	15	15	10
✍ Building component in the open air and building components which are permanently exposed to outside air.	25	20	20	15
✍ Building section in enclosed areas with frequent very high relative humidity at ordinary room temperature, e.g. public kitchen, public bath. ✍ Building section subjected to differing degrees of damp, e.g. in areas with strong condensation. ✍ Building components which are subjected to weak chemical attack.	30	25	25	20
✍ Building components which are exposed to particularly severe corrosive action e.g. permanent exposure to aggressive gases or salts as well as strong chemical attack.	40	35	35	30

2.5.2 Concrete Technology for Corrosion Prevention

Concrete is formed by mixing of three main elements which are cement, coarse and fine aggregates and water. However, research has shown that incorporation of admixtures such as pozzolana or blast furnace slag could improve the durability of concrete as their properties influence the behaviour of fresh and hardened concrete.

2.5.2.1 Cement

It is understood that there are many types cement available in the local market. There are Ordinary Portland Cement and Portland Limestone Cement to name a few. However, there is no single cement that is the best choice under all circumstances. The type of cement selected to be used should at least be suitable for the environment that it is expected to endure. Different cement type gives different early strength, different heat of hydration as well as different curing conditions.

However, special requirement on the chemical composition of the cement may be necessary for certain application in particularly those requiring higher resistance to sulfate attack. For such requirement, incorporation of pozzolanic material or blast furnace could provide the solution as the existence of such additives reduce the rate of development of heat of hydration and produced a denser mix thus improve durability as compared to ordinary cement.

2.5.2.2 Aggregates

Aggregates made up a large portion of concrete (60-85%). They allow reduction of cement content which are relatively expansive as compared to aggregates. Having said so, aggregates contribute to the mechanical properties of concrete such as compressive strength, elastic modulus and wear resistance.

However, not all aggregates are suitable to be blend with cement to produce durable concrete. An aggregate has to of correct size and shape to produce a workable yet durable concrete. Under some circumstances, aggregates can have characteristic that negatively affect durability of reinforced concrete. For instance, they can be susceptible to freeze-thaw attack or contain harmful ions such as sulfates or chlorides.

2.5.2.3 Mixing Water

The main principle in producing a durable concrete is that the water used for concreting must be free of salts or impurities what can interfere with setting and hardening of the cement paste or negatively affect concrete properties.

2.5.2.4 Admixtures

Admixtures are substances that are added during the mixing process in small quantities related to the mass of cement in order to improve the properties of fresh or hardened concrete. Among the common admixtures are superplasticizer that may be added to improve the workability of concrete or in other word, reduce the amount of mixing water.

Admixtures are aimed at increasing the workability of fresh concrete. Superplasticizer are often essential in order to obtain durable reinforced concrete structures. They allow a high workability which is essential to achieve proper compaction of fresh concrete especially in the presence of dense reinforcement. Without increasing the amount of mixing water. The increase in workability is then achieved without changing the w/c ratio and thus without affecting the strength and permeability of concrete.

Superplasticizer can also be used with the purpose of increasing the durability by decreasing the w/c ratio. For instance, they can guarantee the same workability with a remarkable reduction of water, hence, if the amount of cement is not changed, the w/c ratio decreases by the same amount.

2.5.2.5 Mix Design, Mixing, Handling, Placement and Compaction

Concrete has to be designed to fulfill the needs of compressive strength and workability. A mix design is used as a procedure to select the correct amount of concrete constituent such as cement, water, aggregate and admixtures. The mix design provides necessary guideline for the concrete to be designed to the required workability and durability.

Mixing of concrete refers to the blending of correct dosage of cement, water, aggregate and admixtures. A process of stirring these raw materials are done in a mixer for a suitable time in order to obtain a uniform mass. In the case of ready mixed concrete, it is essential to control the consistency of the mix as stiffness of the concrete tends to varies when being transported to places of different distance from the batching plant. There will be a tendency to add water to the mix in order to increase workability. This will lead to an increase in w/c ratio and thus compromising the strength and durability of the concrete.

Placing and compacting of concrete are aimed at filling the form and removing the entrapped air from the fresh concrete. It is preferably the case that the entrapped air is removed as much as possible as lower air in the concrete would produce a less permeable product. Placing and compacting of concrete are extremely important with regard to durability. Excessive voids left after compaction, due to segregation or insufficient vibration affect the permeability of the structure.

2.5.2.6 Curing

Curing of concrete is the process of allowing the hydration of cement paste by controlling the moisture content and the temperature of concrete. The process of curing is normally done by maintaining the concrete saturated with water.

The purpose of curing is to enable the concrete to develop its compressive strength to its full potential. Therefore, if concrete is not kept moist at least in the early stage (3-7 days), hydration is interrupted and the 28-day compressive strength will be much lower than the strength that could be potentially reached. Curing affects both strength and durability, but the consequences of bad curing can be more serious for the latter. Concrete cover is designed with the intention of protecting the reinforcements, however, it is more susceptible to drying out due to evaporation than the bulk concrete. Therefore, the effect of bad curing is bad with regard to the durability of reinforced concrete.

2.5.3 Surface Treatment

The term of surface treatment covers a wide range of materials that can be applied to the surface of a concrete structure which has the ability to protect the structure. Their composition vary from polymeric to cementitious. The major purpose of applying surface treatment is to make the concrete cover zone less permeable to aggressive substances in hoping to prolong the service life of the structure. It is undeniable that surface treatment are very effective in slowing down the penetration of aggressive substances as it usually has good barrier properties. However, the application of such material deal with the risk of losing bond between the treated surface and the concrete as occurance of vapour pressure would take place. Having said so, a right choice of treatment material has to be chosen to minimize the trade-off between good barrier and the loss of bond.

Generally, there are 3 treatment methods available for the local industry:

1. Organic Coatings
2. Hydrophobic Treatment
3. Cementitious Coatings and Layers

2.5.3.1 Organic Coatings

Organic coatings are used to block the penetration of carbon dioxide or chloride ions. They form a continuous polymeric film on the surface of the concrete.

Organic coatings may vary from very dense to rather open for water vapour. Dense coatings are such of those based on epoxy, polyurethane or chlorinated rubber polymers. These coatings help to block ingress of aggressive species. Nevertheless, the presence of such layer strongly hinders the evaporation of the moisture that is present in the concrete at the time of treatment.

Nowadays, open coatings are preferred over dense ones as the open coatings strongly reduce the ingress of water from the environment but allow the evaporation of moisture from the inside.

2.5.3.2 Hydrophobic Treatment

The main objective of applying hydrophobic treatment to concrete surface is to reduce the capillary absorption of water and dissolved aggressive substances. Hydrophobising concrete leaves the pores open, so it does not affect the ingress of gaseous species.

Liquid water is transported rapidly into non-water-saturated pores by capillary suction depending on the surface tension, the viscosity and the density of the liquid, on the angle of contact between the liquid and the pore walls and on the radius of the pores.

The principle behind hydrophobic treatment is that when drop of water is spread on a flat surface, the level inside a capillary will rise above the surrounding liquid and the concrete will absorb the water. The molecular attraction between water and concrete can be weakened by impregnating the concrete with hydrophobic agents suck as silicones, thus making the concrete hydrophobic.

Hydrophobic treatments form a layer of molecular thickness on the concrete pore walls. Because the pores are left open, such treatment does not block transport of single water molecules. The effect, in particular in wetting/drying situations, is that hydrophobic treatment strongly reduce the ingress of liquid water from the environment, but allows the evaporation of moisture from the inside. Consequently the concrete will dry out compared to non-treated concrete.

2.5.3.3 Cementitious Coatings and Layers

Cementitious coatings are layers of low permeability and a moderate thickness of a few millimeters. The mortar or paste used is generally fine grained and modified with polymer to decrease its permeability and to increase its bond to the concrete.

Shotcrete is a form of cementitious coating commonly applied in the construction industry. Shotcrete is in fact fine-grained concrete with a high cement content and low w/c ratio with addition of silica fume, which is very dense due to the high impact that goes with the application method.

A layer of shotcrete is generally considered as additional concrete cover, because the high-density material has comparable or even better durability and mechanical properties than the original concrete cover.

2.5.4 Corrosion Resistant Reinforcement

When a structure is expected to endure in conditions of high environmental aggressiveness or when a long service life is required, reinforcing bars with a higher corrosion resistance than the common carbon steel rebars can be used as a preventative measure.

The corrosion resistance of rebars are increased by modifying the chemical composition of the steel or by applying a metallic or organic coating on their surface. The three types of corrosion resistant rebars which are commonly found as replacement of carbon steel are:

1. Stainless steel
2. Galvanized steel
3. Epoxy coated rebars

2.5.4.1 Stainless Steel Rebars

Stainless steel is an extended family of steel types with a wide variety of characteristic with regard to physical and mechanical properties, cost and corrosion resistance. A layer of chromium-rich passive film present on their surface enables it to have higher corrosion resistance than carbon steel. The application of stainless steel rebar is normally introduced to structures that are exposed to aggressive environments, especially in the presence of chlorides. They can also be selectively used in those parts of structures where corrosion is most likely to occur and in the repair of corroding structures.

As mentioned above, the use of stainless steel rebars is normally associated with chloride bearing environments rather than under the threat of carbonation. Pitting is the only form of corrosion expected on stainless steel in concrete. Stress corrosion are unlikely to occur since it only take place under conditions of high temperature, carbonated concrete and heavy chloride contamination. The corrosion resistance of stainless steel is affected by the presence of mill scale on their surface, this is normally removed by pickling or sandblasting.

Generally, stainless steel reinforcement can be a applied in order to prevent corrosion. These rebars can be used in the more vulnerable parts of structures exposed to chloride environments such as joints of bridges or the splash zone of marine structures. In the mean time, they can be used when the thickness of the concrete cover has to be reduced, such as in slender elements.

However, the major restriction of wide application of such rebars is the cost factor. The application may have a significant impact on the cost of a structure. Although the cost of the material has decreased in recent years and further reductions are expected due to new development in production, cost of stainless steel are still much more expensive than carbon steels.

However, several authors have shown that by applying life-cycle cost analysis to several types of structures exposed to a chloride environment, the choice of a suitable type of stainless steel in specific parts of the structure can allow savings on future maintenance expenses that can be much higher than the initial increase in cost.

2.5.4.2 Galvanized Steel Rebars

Differing from stainless steel rebars, galvanized steel rebars can be used as a preventative measures to control corrosion in reinforced concrete structures exposed to carbonation and mild contamination with chlorides. Advantages of using galvanized reinforcement are significant compared to carbon steel under equivalent conditions. Among the advantages are:

1. An increase of initiation time of corrosion,
2. Greater tolerance for low cover,
3. Corrosion protection is offered to the reinforcement prior to it being embedded in concrete.

Galvanized bars are produced by the hot-dip galvanizing process. Pickled steel bars or welded cages are dipped in a bath of molten zinc at a temperature of about 450C. This process produces a metallic coating composed of various layers of iron-zinc alloys, which has a metallurgical adhesion to the steel substrate. An external layer of pure zinc, left by the simple solidification of the liquid metal, is formed on top of a sequence of inner layers, increasingly rich in iron, which are the result of formation of brittle intermetallic compounds.

Galvanized reinforcement are said to be applicable for corrosion caused by carbonation as the passive film of galvanized rebars is stable even in mildly acidic environment so that the zinc coating remain passive even when the concrete is carbonated. Furthermore, the corrosion rate of galvanized bars remains negligible in carbonated concrete even if a low content of chloride is present. However, cautious must be practiced in the sense that cracks in the zinc coating must be avoided and microscopic defects have to be repaired prior to casting as the passive zinc coating is not able to provide active protection to steel and consequently not able to reduce the corrosion rate in the areas of the steel that are not protected.

Similar to stainless steel, cost remains the biggest factor from restricting the wide application of galvanized steel in local construction industry. It was quoted that the price of galvanized bars is about 2 to 2.5 times the price of normal black steel bar.

2.5.4.3 Epoxy Coated Rebars

Epoxy coating of reinforcing bars is not something new to the industry. The protective technique was developed in 1970s in North America. Laboratory results confirmed the effectiveness of the epoxy coated bars especially for preventing corrosion of reinforcement in carbonated or chloride contaminated concrete.

Protection of rebars by organic coatings is based on the principle of insulating the steel and protecting it from aggressive agents that penetrate the concrete cover. The use of coated bars does not affect the structural design and also construction of the structure.

Epoxy coated bars is not completely impermeable to oxygen, water and chlorides, it does, however, provide guarantee protection against reinforcement corrosion in chloride-contaminated concrete. The level of protection provided is proportionate to the thickness of the coatings.

However, in recent years there has been very serious case of corrosion damage in some structures in tropical areas where severe attack of epoxy-coated steel has been observed. This situation has led contractors and designers to reconsider the widespread use of this technique on structures exposed to chloride-bearing environments. Serious doubts have been expressed about whether epoxy coatings, even in the absence of any damage, can insure long-lasting protection in heavily chloride contaminated and hot environments, particularly when the concrete is frequently wetted.

2.6 Methods of Repair

2.6.1 Conventional Repair Method

The term conventional repair is used to indicate a repair work made on a damaged reinforced concrete structure, which is aimed at restoring protection to the reinforcement by means of replacement of non-protective concrete with a suitable cementitious material. The work for a typical conventional repair can be divided into:

1. Assessment of the condition of the structure.

2. Removal of concrete in well-defined parts of the structure and for a specified depth.
3. Cleaning of the exposed rebars.
4. Application of suitable repair material to provide an adequate cover to the reinforcement.

2.6.1.1 Assessment of the Condition of the Structure

The cause of structure failure due to corrosion must not be overlooked when conventional repair method is to be applied. The causes of deterioration and the condition of the structure have to be clearly assessed, otherwise any repair work could only be considered a waste of time and money. For the corrosion of rebar to be effectively repaired, a survey of the structure has to be carried out with the aim of identifying the extent of the areas where concrete has to be removed and the depth that should be removed. In other word, a clearly described working plan of the repair should be made.

2.6.1.2 Removal of Concrete

Removal of concrete in order to provide maximum protection to the reinforcement after the repair work does not limit to the zones where it is weak, cracked or damaged. Removal of structurally sound concrete is often necessary if carbonation or chloride contamination is expected to damage the structure. However, it is a norm for common practice to neglect the importance of removing undamaged concrete.

Major problem arise from the application of conventional repair technique is the bonding strength of the repair material against the surface of the removed concrete. Factors that may affect the bond are the strength and integrity of the substrate, the cleanliness of the surface and the roughness. Ideally, the surface should be free from dust or incoherent residue that might affect the bonding strength. In come cases, bonding agents such as cement paste or fine mortar, polymer latex and epoxy system could proved handy in order to enhance adhesion of the repair mortar.

2.6.1.3 Preparation of Reinforcement

The major operation for preparing the reinforcement is to remove the loose rust as well as fine mortar that could compromise bonding strength with the repair material. Effective way of achieving satisfactory level of cleanliness of the reinforcement is by applying mechanical method or sandblasting.
However, cleaning of the reinforcement surface requires special attention when the concrete is contaminated by chlorides. It is not enough to eliminate only the loose rust as small amount of chlorides could cause re-activation of corrosion. Therefore, chloride-containing corrosion product needs to be removed completely. This is usually achieved only by means of high-pressure water blasting.

2.6.1.4 Application of Repair Material

A repair material suitable to protect the reinforcement during the required design life span should be determined. Among requirements needed to take into consideration in order to achieve the goal is the alkalinity and resistance to carbonation and chloride penetration of the material. Beside that, the cover thickness should also be designed such as to provide sufficient protection for the reinforcement for a required time.

2.6.2 Cathodic Protection

Cathodic Protection can only be applied when a metal is exposed to an electrolytically conducting environment. Therefore it is only limited to aqueous environment and applied on aqueous corrosion.

As discussed before, an anodic reaction of :

$$Fe \longrightarrow Fe^{2+} + 2e^-$$

would occur at the anode once steel in concrete starts to corrodes. It dissolves into pore water and gives up electron. For the law of electrical neutrality, the two electron created from the anodic reaction must be consumed elsewhere on the steel surface. For this, a cathodic reaction of :

$$2e^- + H_2O + ?\ O_2 \longrightarrow 2OH^-$$

would occur. This reaction not only consumed 2 electron but as well as H_2O(water) and O_2(oxygen).

Le Chatelier Principle suggested that if an electrical intervention is forced in the corrosion reaction of :

Anodic : $Fe \longrightarrow Fe^{2+} + 2e^-$

Cathodic : $2H^+ + 2e^- \longrightarrow H_2$

the rate of corrosion might be disturbed. Therefore, based on the theory of Le Chatelier's Principle, the method of cathodic protection is explained by applying an external power source in hoping that the electron consumption would speed up while the electron release reaction would slow down [1].

Cathodic protection provides one of the most effective and practical way for reducing the corrosion rate to zero. It is accomplished by supplying an external current to the corroding metal, on the surface of which local action cells operate. The current leaves the auxiliary anode of a power supply (cell) and enters both the cathodic and anodic area of the corrosion cells, returning to the source of DC supply.

When the cathodic potential of the anode, all the metal surface is at the same potential and local-action current no longer flows. Therefore, as long as the external current is maintained, the metal would not corrode.

2.6.2.1 Application of Cathodic Protection on Reinforced Concrete Structure.

For a carefully designed and constructed concrete structure, the embedded steel are under protection from corrosion damage as the naturally highly alkaline cement provides a passivating environment. Even under aggressive condition a well compacted, good quality with adequate cover will completely prevent corrosion of steel for years. However, such mentioned construction criteria are rarely met in the industry. Therefore, application of electrochemical repair technique are required for critical structures, especially those that are exposed to corrosive environment.

a. Due to uncertainty of design and poor workmanship, cases of inadequate cover would caused the structure more prone to mechanical damage that might trigger corrosion process.
b. Substructure such as foundation, buried water tank and concrete pipeline are hard to perform maintenance work on it. By applying cathodic protection, the rate of corrosion would slow down or stop, therefore needing only minimum maintenance.

2.6.2.2 Types of cathodic protection

There are two cathodic protection methods that are applied in the field of engineering namely sacrificial anode method and impressed current method. However, this thesis would only focus on the impressed current method as it has a better principle approach on the theory of cathodic protection.

Conventional impressed current method works by supplying a controlled direct current (DC) to the system. This proved to be costly as the alternative current (AC) from domestic electric source need to be converted to direct current by a transformer rectifier.

Furthermore, the conventional method is maintenance bound meaning frequent repair works are needed to ensure the serviceability of the system.

Therefore, on 22 March 1998 the National Association of Corrosion Engineers (NACE) has reached an agreement that alternative source are to be sought to lighten or solve the problem arising from the using of domestic electric for cathodic protection system [14]. In this case, solar photovoltaic energy seems most appropriate.

2.6.2.2.1 Sacrificial Anode

This method directly connects the reinforcement bar to a sacrificial anode such as zinc without the use of power supply. Figure 2.9 illustrate a typical cathodic protection system using sacrificial anode.

Because of its low driving voltage characteristic, application of this method is more suitable form protection of steel under high moisture content condition where environmental resistivity is lower.

The principle advantage of this method is that the system is cheaper to build and easier to run. Since current and voltage cannot be regulated, therefore monitoring requirements are at its minimal.

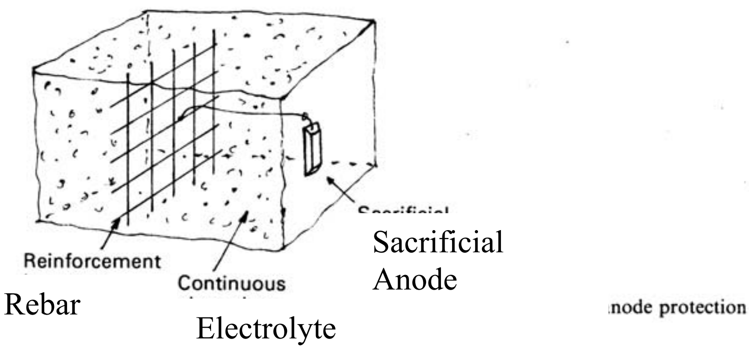

Figure 2.9 Sacrificial anode protection.

2.6.2.2.2 Impressed current method

This technique works by delivering a small electrical current (DC) from a direct current source through an auxiliary anode to the surface of the reinforcement as shown in figure 2.10. It will act as cathode while the auxiliary electrode would become an anode in the cell. The metal based electrode is normally made of ferum (Fe).

With the presence of water in concrete pores as electrolyte, it triggers the hydrogen evolution reaction. The reaction at anode of :

$$Fe \longrightarrow Fe^{2+} + 2e^-$$

would contribute two electrons while the reaction at cathode of:

$$H_2O \quad + \quad \text{瞌}_2 \quad + \quad 2e^- \quad \longrightarrow \quad 2OH^-$$

consume the electrons.

The generation of hydroxyl ions at cathode will increase the alkalinity hence helps to rebuild the pa:

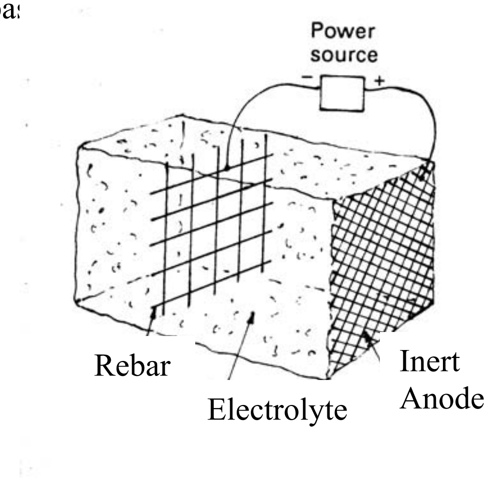

Figure 2.10 Impressed current protection.

2.6.2.3 Cathodic Protection of Steel in Chloride-contaminated Concrete

According to Nernst’s law, it is suggested that immunity conditions is not necessary in order to achieve cathodic protection of steel reinforcement embedded in chloride-contaminated concrete. By providing a small amount of current and small reduction in potential, the corrosion rate can be reduced as the protection system takes the steel into the passivity range or by reducing the macrocouple activity on its surface. For reinforced structures that are exposed to atmosphere, current density in the range of 5-15 mA/m? is recommended. However, the current required decreases when the structure is submerged into water whereby the access of oxygen is reduced. For elements operating under water, current densities typically in the range of 0.2 to 2.0 mA/m? are sufficient.

2.6.3 Cathodic Prevention

Similar to cathodic protection, cathodic prevention is a method of preventive maintenance of new structures that are expected to become affected by chloride contamination. The difference between this type of repair method and cathodic protection is that it has aims, operating conditions, throwing power, effects especially important for those regarding hydrogen embrittlement, involved many engineering and economic aspect that is connected with design, construction, monitoring and maintenance.

The principle of this technique is that the chloride threshold increases as the potential of steel decreases. In, practice, application of very low current densities (<2mA) can bring the potential to values in which steel operates in conditions of "imperfect passivity" so that initiation of pitting is suppressed even if high levels of chlorides, penetrating through the cover concrete, build up at the surface of the steel. The mechanism of work for cathodic prevention is as illustrated in Fig.2.11.

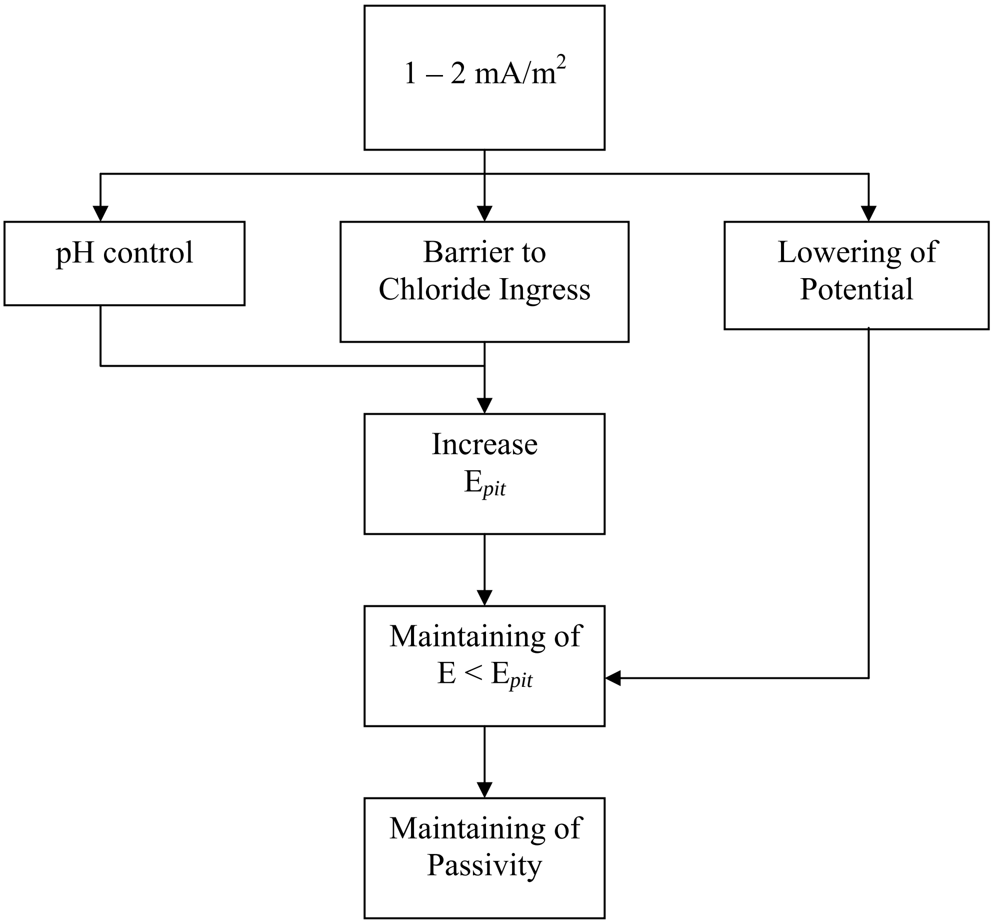

Figure 2.11 Mechanism of Cathodic Prevention

This technique is commonly being applied in conjunction with conventional patch repair of chloride-contaminated structures in order to avoid the initiation of incipient pitting around the repaired zones, by utilizing sacrificial anodes embedded near the periphery of the repair patches.

2.6.4 Electrochemical Chloride Removal

As the name of the method suggested, this method of repair involves removal of chloride ions from concrete by an electrochemical process using a liquid electrolyte and very high direct current (DC) voltage (>220 V).

Direct current is applied between the reinforcement, in which will be cathode, and an anode that is placed temporarily on the outer surface of the concrete. The anode is an activated titanium wire mesh or a reinforcing steel mesh. The anode is surrounded by tap water or saturated calcium hydroxide solution in ponds (upper, horizontal surfaces) or tanks (vertical or overhead surfaces) or as a paste that can be sprayed onto all types of surface. Chloride ions migrate from the reinforcement to the anode. Due to a relatively high current density of 1 to 2 A/m^2, relatively large amounts of chloride can be removed from the concrete within a relatively short time, usually 6 to 10 weeks. The anode, electrolyte as well as the chloride ions are then removed from the structure. The principle layout and electrode reactions involved are indicated in Fig.2.12

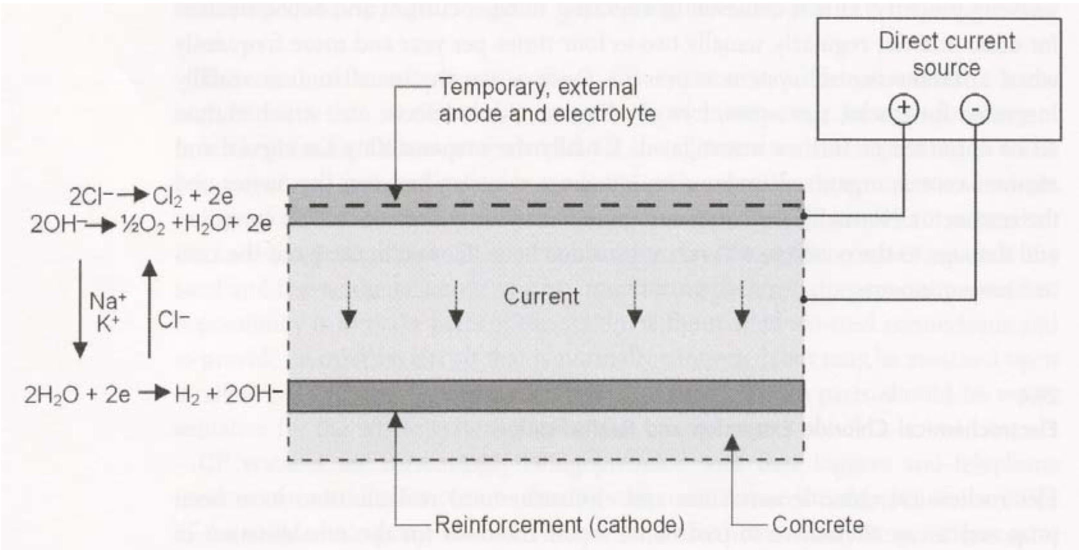

Figure 2.12 Principle reactions involved in chloride extraction.

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2.6.5 Electrochemical Realkalisation

Electrochemical realkalisation of steel reinforced concrete as a corrosion repair method has been introduced in the late 1980s by Noteby. The original system used a surface-mounted steel mesh anode and sprayed paper pulp wetted by sodium carbonate solution as the electrolyte. Later on, the application of titanium mesh anode and liquid electrolyte were introduced. Development of the technique was later on conducted by Ciment d'Obourg and Fressyinet to explore the possibility of applying sacrificial anode method.

The operating mechanism of this technique is similar to that of chloride removal. Fig 2.13 below illustrate the mechanism of electrochemical realkalisation.

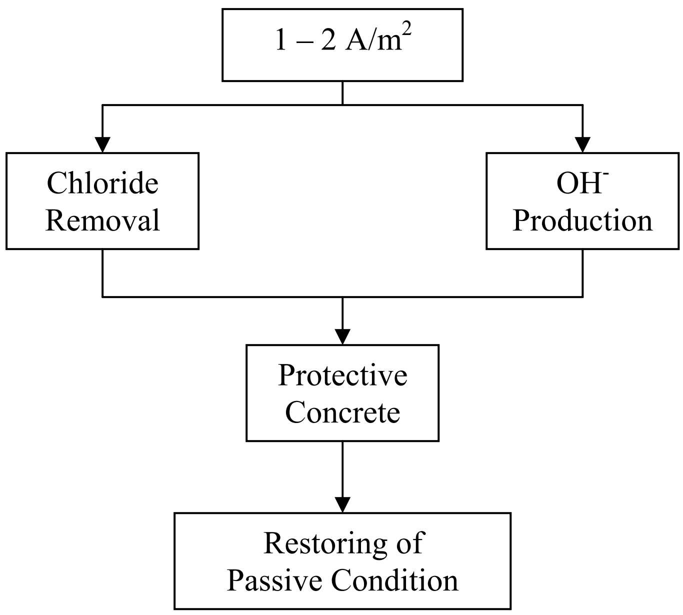

Figure 2.13 Mechanism of electrochemical realkalization.

A direct current (DC) is applied between the reinforcement (cathode) and an anode that is placed temporarily on the outer surface of the concrete. Titanium mesh of reinforcing steel mesh is normally used as the anode. The anode is surrounded by a sodium carbonate solution of about 1 mole per litre in pond (upper, horizontal surfaces) or tanks (vertical or overhead surfaces) or as a paste that can be sprayed onto all types of surface. The layout and principle reactions involved are indicated in Fig. 2.14.

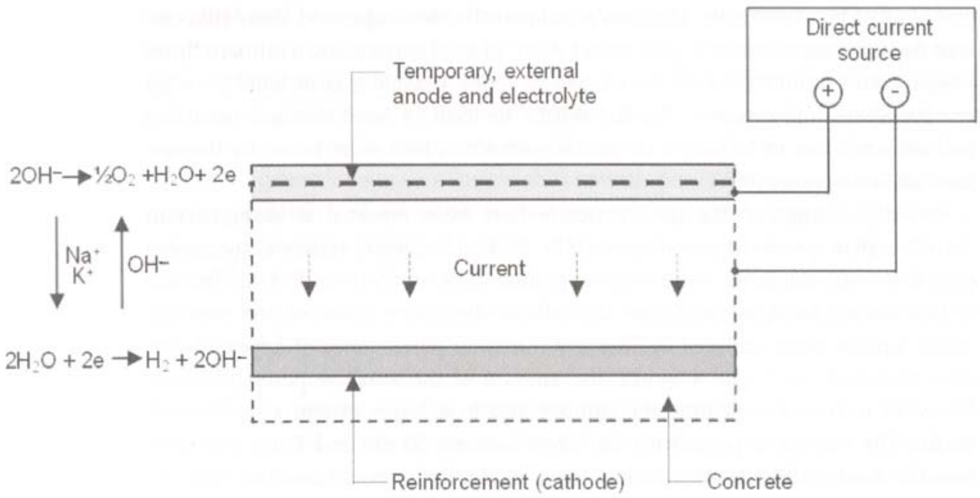

Figure 2.14 Principle of electrochemical realkalisation.

2.7 Economic Analysis

2.7.1 Cost of Corrosion

As mentioned before, corrosion management includes all activities carried out throughout the service life of the structure to mitigate corrosion, to repair corrosion-induced damage, and to replace the structure, which has become unusable as a result of corrosion. In other word, it can be defined as a maintenance activity to prolong the service life of a structure. It is understood that maintenance operation usually cost a large sum of money. Therefore, a proper approach is very much needed to ensure that the money invested would generate reasonable result. Hence, various methods have been established to determine the cost-benefit ratio for the sector.

This approach takes into consideration the initial cost of a certain organization needed to spend on corrosion preventing. It will then determine the benefit of corrosion management in terms of extending the service life and functionality of the protected structure or facility. Since these costs occur at different times during the service life of the structure, they are annualized in order to make them comparable. Savings made by changing from current corrosion management practices to more cost-effective practices point out the possible benefits of optimized corrosion management. Determination of the most cost effective practices was based on the evaluation of the current practices. Thus, savings are possible if the annualized cost of the most cost-effective corrosion management strategy is lower than that of the current practice.

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2.7.2 Direct and Indirect Cost

Basically, there are two types of cost involved in the calculation of economic analysis for corrosion management, namely direct cost and indirect cost. Direct cost can be defined as the cost required to perform the maintenance work and are usually bear by the owner of the facility or structure. Whereas the indirect cost are usually linked with the cost needed for the continuity of maintenance work.

Every different approach or method applied to curb the problem of corrosion would generate different cost. Therefore, in order to accurately estimate the cost of corrosion prevention, it is important to include both the above cost. Among the critical indirect cost that would generate large amount of sum are the costs of delays, service interruption, or environmental damage. The design with the lowest annualized cost is then the design with the lowest cost of providing the service to the entire society.

2.7.3 Life Cycle Cost

Life Cycle Cost or LCC for an item can be defined as the cost that would involve throughout the life span of it. An item can be either an asset, machine, plant or a project. In other word, Life Cycle Cost for corrosion management starts as soon as the activity to determine the requirement of the client takes place while the ending point would be the termination of the project or program.

LCC analysis is used in this project to assess corrosion management alternatives. It determines the Annualized Value (AV) of each option, which is used to compare the alternatives. Since in the analysis it is assumed that all options meet the same service requirement, the lowest cost option is therefore the most cost-effective option to achieve the service requirement.

It must be reminded that the evaluation for alternative methods should not be made based on their initial cost. For example, it costs less to build an uncoated carbon steel pipe (first option) than a coated carbon steel pipe (second option); however, the coated pipe would last longer. Therefore, for the correct comparison, the construction cost must be annualized over the entire service life of the pipeline. A comparison of the two options is therefore based on the annualized value of each. Current Cost

In a layman's term, current cost is defined as a cost based on the prevailing price paid for material, labor, etc. However, in the case of corrosion management, current cost of corrosion is referred as the sum of the corrosion-related costs of design and construction/manufacturing; the cost of corrosion-related maintenance, repair, and rehabilitation (corrosion management); and the cost of depreciation or replacement of structures that have become unusable as a result of corrosion.

Determination of the current cost of corrosion is carried out in the following steps:

1. Determine the cash flow of corrosion-related activities: describe corrosion management practices (materials, actions, and schedule), determine the elements of corrosion cost.
2. Calculate present discounted value (PDV) of the cash flow.
3. Calculate Annualized Value for the PDV.

2.7.4 Cash Flow

Theoretically speaking, cash flow represent the inflow and outflow of cash in a linear manner. As mentioned above, it is understood that corrosion management should take into consideration both the direct and indirect cost; therefore, the corrosion-related cash flow of a structure/facility includes all costs, direct and indirect, that are incurred due to corrosion throughout the entire life-cycle of the structure.

Different approaches to the design and maintenance of corrosion prevention would generate different cost which at times, vary greatly between them. One approach to determine the total corrosion cost is to extrapolate from a typical corrosion cost to the entire sector.

As mentioned previously, the cost of corrosion can be divided into direct and indirect cost. Examples of some direct cost are:

a. Amount of additional or more expensive material used to prevent corrosion damage, multiplied by the (additional) unit price of the material.
b. Number of labor hours attributed to corrosion management activities, multiplied by the hourly wage.
c. Cost of the equipment required as a result of corrosion-related activities.

Examples of indirect cost are as follows:

a. Increased costs for consumers of the product (lower product supply on the market results in a higher cost to consumers) or lost time due to the search for the alternative goods/service.
b. Effect on local economy (loss of jobs).
c. Effect on the natural environment by pollution.

2.7.5 Present Value

Structures were designed to serve for a period of time which referred to as service life. Generally, more than one option can be utilized to satisfy the service level for the required service life. In other word, once the cash flow for the service life is determined, the value of each option can be calculated. A typical cash-flow cycle (a complete life-cycle) is as follows:

a. Year Zero -- Direct cost is the total initial investment of constructing a new structure or facility. If there is an old structure, its removal cost is not included. There is a user cost associated with the construction of a new structure. If there is an old structure, the user cost associated with its removal is not included.

b. During Service -- Direct cost includes all costs associated with maintenance, repair, and rehabilitation. The user cost can be generated by the worsening conditions of the structure that reduces the level of service of the structure during any maintenance, repair, or rehabilitation.

c. Last Year -- Direct cost includes all costs of structure removal. If the old structure is replaced with a new one, the cost of the new structure is not included. There is a user cost associated with the removal of the structure. After the removal of the old structure, a new life-cycle begins.

All materials and activities incurring corrosion-related costs during the service life of the structure must be identified, quantified, and valuated. Direct costs of the corrosion management activities, or the cost to the owner or operator, include material, labor, and equipment costs. (The price of labor, material, and equipment are assumed to be the same for all design and all corrosion management alternatives.) As stated earlier, all indirect costs should be accounted for as well. For example, if a corrosion-related maintenance activity on a bridge deck requires traffic maintenance, its cost needs to be included.

The corrosion management schedule of the structure determines the direct-cost cash flow. Calculation of the present value of the cash flow entries is presented in the following sections.

The initial investment occurs in the "present"; therefore, no discounting is necessary. Annual maintenance is assumed to be constant throughout the life-cycle of the structure. Thus, the present discounted annual value PDV{AM} is calculated back to the present as follows:

$$PDV\{AM\} = AM\ ?\ [1 - (1 + i)^{-N}] / i$$

Where, AM = cost of annual maintenance (RM per year)

N = length of service life in years

i = interest rate

For the calculation of the present value of activities that grow annually at a constant rate (**g**), a modified interest rate needs to be calculated using the following formula:

$$i_0 = (i - g) / (1 + g) \text{ and } i > g$$

Where, i_0 = modified interest rate

i = interest rate

g = constant annual growth rate

If the first payment (P1) occurs in year one, the present value of a cash flow that grows annually at a constant rate over **n** years is calculated using the following formula:

$$PV\{P\} = [P_1 / (1 + g)]\ ?\ [1 - (1 + i_0)^{-n}] / i_0$$

PV{P}, the present value of a cash flow series that starts at P1 in year 1 and grows at a constant rate **g** for **n** years when interest rate is **i**, is equivalent to the present value of an annuity of $[P_1 / (1 + g)]$ for **n** years when interest rates are $\mathbf{i_0}$, where $\mathbf{i_0}$ is given by the equation above.

The first payment for repair activities, however, usually does not occur in year one, but, rather in year **t**; therefore, the above formula calculates the value at year **(t-1)** discounted back to year zero of the life-cycle to determine the present discounted value of the repair:

$$PDV\{P\} = PV\{P\} ? (1 + i)^{-(t-1)}$$

The PDV of one-time costs, such as one-time repairs (R), rehabilitation (RH), or removal of an old structure (ROS) is calculated as follows:

$$PDV\{R\} = R ? (1 + i)^{-tR}$$

$$PDV\{RH\} = RH ? (1 + i)^{-tRH}$$

$$PDV\{ROS\} = ROS ? (1 + i)^{-tROS}$$

Where, R = cost of the repair

RH = cost of the rehabilitation

ROS = cost of removing the old structure

t = year in which the cost is incurred

The present value (PV) of alternatives is calculated as the sum of the PV of its cash flow added to the initial capital investment (I):

$$PDV = I + PDV\{AM, P, R, RH, ROS\}$$

2.7.6 Annualized Value of the Cash Flow

In calculating the service life cost of alternative corrosion management approaches, the irregular cash flow of the entire service life is transformed into an annuity (a constant annual value paid every year) for the same service life. The annualized value (AV) of the alternative approach is calculated from the PV by use of the following formula:

$$AV = PDV \text{ ? } i / [1 - (1 + i)^{-N}]$$

The annuity of the initial investment (I) made in year zero is determined such that its present discounted value is equal to the present discounted value of its annuity:

$$PDV\{I\} = PDV[A\{I\}] = \Sigma_{n=1}^{N} [A\{I\} / (1+r)^{N}]$$

Where, A{I} = annualized value of the capital investment

A{CM} = annualized value of all corrosion management costs

r = annual discount rate

n = service year, n = 1… N,

N = entire service life

PDV{I} = present discounted value of the initial investment

PDV[A{I}] = present discounted value of annuity of the initial investment

The actual corrosion management costs throughout the “n” years of the structure’s service life will fluctuate. The fluctuating cash flow is replaced with an equivalent uniform cash flow of its annuity. The annuity of the corrosion management yearly cash flow is determined such that the present discounted value of the original cash flow is equal to the present discounted value of the annuity:

$$PDV[A\{CM\}] = PDV\{CM\} = \Sigma_{n=1}^{N} [A\{CM\} / (1+r)^{N}]$$

Where, PDV{CM} = present discounted value of the original cash flow of corrosion management

PDV[A{CM}] = present discounted value of the uniform cash flow or annuity

The annuity of the original cash flow is then:

$$A = A\{I\} + A\{CM\}$$

This annuity or “annualized cost” is a constant annual value paid every year; present discounted value is equal to the present discounted value of the irregular cash flow for the entire service life of the structure.

In summary, the current cost of corrosion is the sum of the amount spent preventing corrosion at the design and construction phase; the amount spent on maintenance, repair, and rehabilitation to control and correct corrosion (cost of corrosion management); the amount spent on removing and replacing structures that become unusable due to corrosion (depreciation or cost of replacement); and the indirect (user) cost generated by or during these activities.

2.7.7 Potential of Cost Saving Through Corrosion Management

The main goal of corrosion management is to achieve the desired level of service at the least possible cost. There is a range of current practices of dealing with corrosion, yet, one could be the most cost effective while others could be improved to be more cost effective as while. Therefore, the importance of the study is to answer to the question of how to lower the current cost of corrosion through improvement of the program.

Finding the corrosion management program that has the greatest net benefits to society requires a careful analysis of all the direct and indirect cost involved. This analysis requires specific corrosion-related cost information. Unfortunately, because of the complexity of corrosion control and management issues or the reluctance of the experts to share the data, for many industrial sectors, insufficient information was available to identify the design-maintenance option that had the lowest annual cost.

CHAPTER III

METHODOLOGY

3.1 Introduction

General corrosion prevention program adopted by local contractors are required to determine the current trend of corrosion management for concrete reinforced structures. On top of that, information from local developers are needed to further understand the cost of maintenance subjected to corrosion of concrete reinforced structures. Therefore, it requires proper planning of methodology to achieve the objectives of the study. Figure 3.1 refers to the flowchart of the methods in achieving the mentioned objectives of this study.

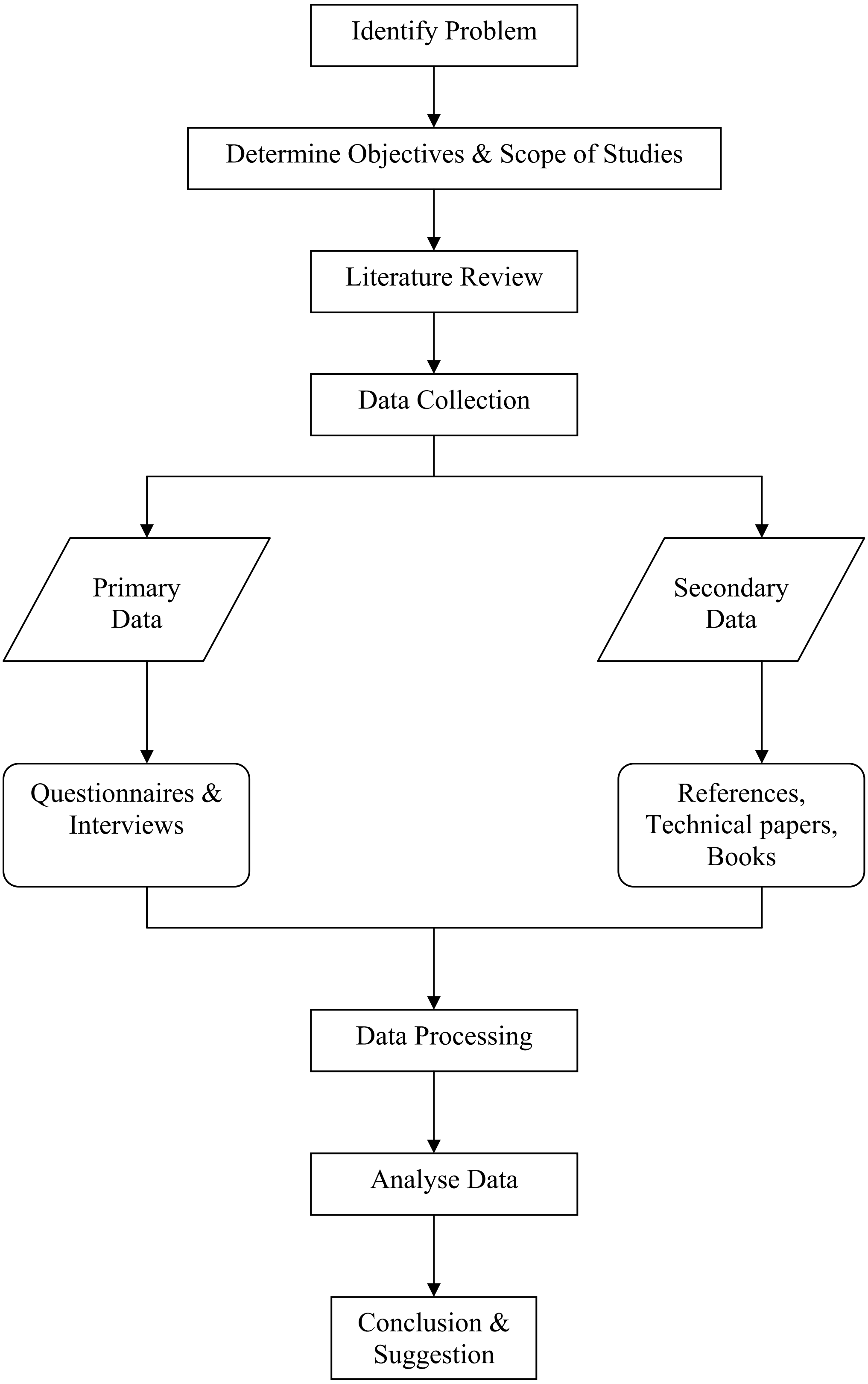

Figure 3.1 Methodology Flowchart

This section of study would focus on the method of study to be carried out to achieve the objective of this report. Therefore, every measure taken must be appropriate and relevant to the related topic of study.

Three approaches has been throughout this study to gather reliable and relevant data. The approaches are:

i. Literature review
ii. Handing out of questionnaire
iii. Interviews with contractor
iv. Case study.

3.2 Literature Review

Literature review is an important part in the study in terms of gathering secondary data. Important and resourceful information can be obtained for further understanding of the study. For this, it has helped to achieve the objective to understand the method applied to estimate the cost benefit ratio related to corrosion management.

3.3 Questionnaire

Handing out questionnaire is an approach to determine the current development in terms of corrosion prevention being practiced among contractors, developers and consultant in Malaysia. It was designed to gather information which is not available from literature review.

Generally, two approaches of questionnaire has been handed out, namely quantitative approach and qualitative approach. Quantitative approach, in short, is a systematic way of questionnaire where corresponding parties are required to complete the questionnaire by answering one or more answer from a list of given alternatives. The statistical report, can therefore be generated.

Whereas, for qualitative approach, questions are set in the form of semi-structured or non-structured. Semi-structured questions require the respondent to complete a list of questions based solely on their experience and opinion. As for the non-structured questions, the respondents are required to explain subjectively the answer given by them.

Questionnaire is an effective way for the purpose of gathering information and data that are not available through literature studies. However, the limitation of questionnaire is that it is subjected to the willingness and cooperation of the respondent in completing the questionnaire. Therefore, it is necessary to design the questionnaire as straight-forward as possible to obtain information related to the objectives of the study. Another important criterion when designing the questionnaire is the time to complete it. It should be designed to be completed in the shortest time possible for the convenience of the respondent as the workload of a developer, contractor or consultant is usually heavy.

3.4 Methods of Analysis

The information and data gathered through questionnaire will be compiled and processed using average index method in relation to the objectives and scope of study. Two statistical methods will be applied, namely descriptive statistic and inferential statistics. Result from the findings will be presented in the form of graphs, histogram and pie chart for easier understanding.

3.4.1 Average Index

Average index is being calculated based on the formula of:

$$\text{Average Index} = \frac{\sum aixi}{\sum xi}$$

Where, a = constant, weighing factor for i,

x = frequency of respondent

i = 1, 2, 3……n

A scale of 5 categories has been used for the average index method in order to show priority. The scales of 5 categories are:

1 =	"Most prior"	$1.00 \leq$ Average < 1.50
2 =	"Prior"	$1.50 \leq$ Average < 2.50
3 =	"Moderate prior"	$2.50 \leq$ Average < 3.50
4 =	"Less prior"	$3.50 \leq$ Average < 4.50
5 =	"Most least prior"	$4.50 \leq$ Average < 5.00

3.4.2 Mean

The collected raw data are required to be separated in a table of frequency. Basically, mean is the average value of a group of data. The formula for the calculation of mean is:

$$\text{Mean, x} = \frac{\sum_{i-1}^{n} fix}{\sum_{i=1}^{n} fi}$$

Where, f_i represent the frequency of class where x_i is the sign of class.

3.4.3 Median

Median can be defined as the middle number of a group of number that have been arranged in order. In other word, median represent a value where half of the total collected data are either larger or smaller than its value.

The formula for the calculation of median is:

$$\text{Median, X} = \text{Lm} + \frac{\frac{\sum_{i=1}^{n} fi}{2} - \sum fm - 1}{fm}(C)$$

Where, $\sum_{i=1}^{n} fi$ = Total frequency,

Lm = Border of lower class that consist of median,

fm = Frequency of data in the class that consist median,

$\sum fm - 1$ = The collected frequency of class before that consists median.

C = The size of the class that consist median.

3.4.4 Mod

Mod represent the highest frequency of the value in a group of data. In such cases where repeatation of value doesn't exist, the group of data is considered as no mod.

The value of mod can be determined from either histogram or calculation by applying certain formula. The formula for mod is:

$$\text{Mod} = \text{Lm} + \frac{(\Delta 1)}{\Delta 1 + \Delta 2} \times C$$

Where, Lm = the border of lower class that consists of mod,

$\Delta 1$ = difference of frequency between the class of mod and the class before

$\Delta 2$ = difference of frequency between the class of mod and the class after it.

C = the size of class that consist of mod

CHAPTER IV

RESULTS AND DISCUSSIONS

4.1 Introduction

Primary data was collected through the process of conducting questionnaire as well as interviews with the respondents. Meanwhile, secondary data was the result of conducting literature reviews. The data collected from the questionnaire are presented in a statistical way.

4.2 Number of Respondent

A total of 45 (forty five) copies of questionnaire were distributed to consultants, contractors as well as developer in the area of peninsula Malaysia. However, only a total of 22 copies of questionnaire were completed and sent back. Figure 4.1 indicate that only 49% of the questionnaires were sent back while the respond for the rest of it were negative. Thorough checks through the questionnaire indicate that most of it were positively filled and was legible for further analysis.

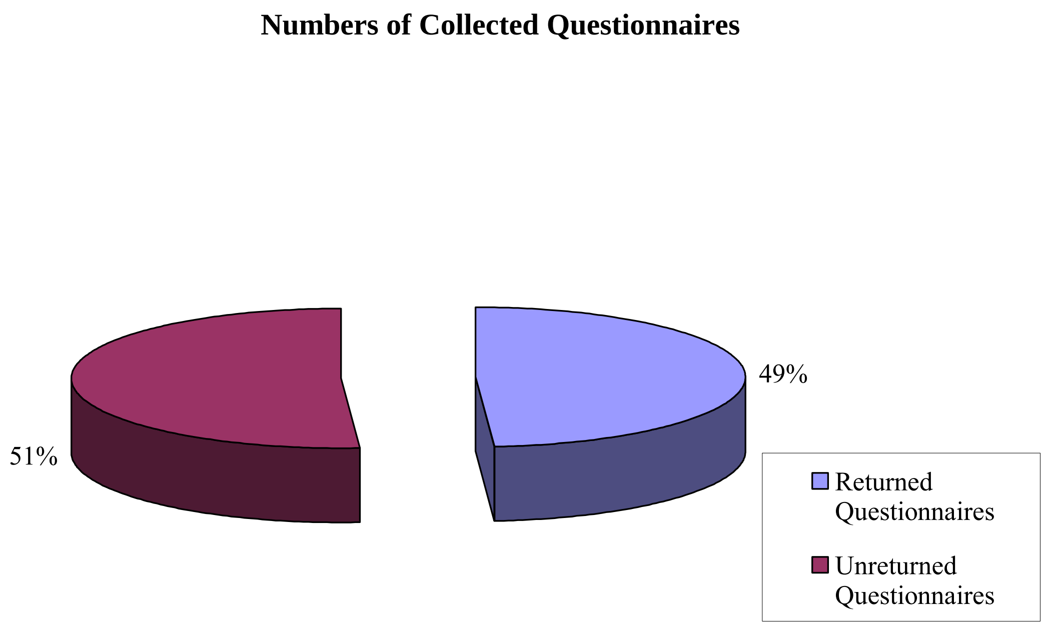

Figure 4.1 Numbers of collected questionnaires

4.3 Fields of Expertise of Respondents

From the 16 questionnaires received, it was found that 16 respondents involved in providing consultancy work where as 3 are contractors and the others are developers. Figure 4.2 is the graphical presentation indicating the field of expertise of the respondents.

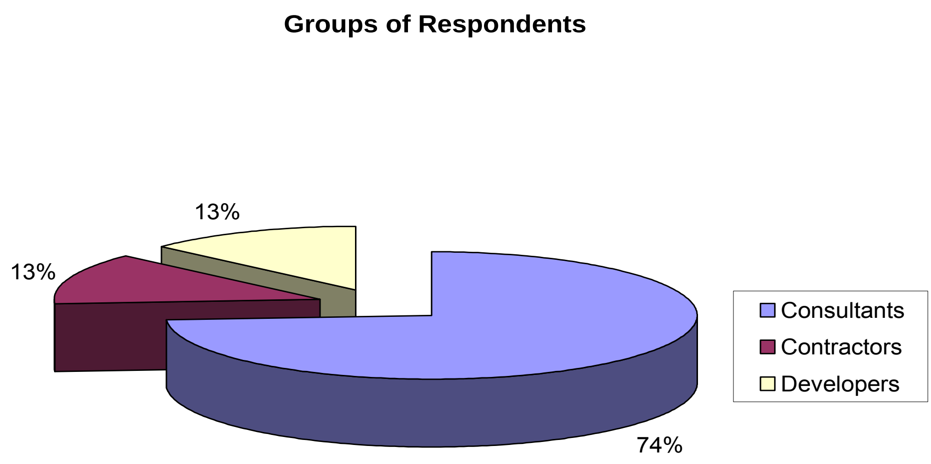

Figure 4.2 Fields of expertise of the respondents

4.4 Experience of Respondents

Figure 4.3 indicates the years of working experience from the respondents.

Figure 4.3 Working experience of respondents

4.5 Cost of Steel in Construction

The main reason to conduct survey on the percentage of the cost of steel in construction indicates the significance of steel in the industry. The feedback from the respondent are indicated in Figure 4.4.

From the graph, it proved that most respondents share a common opinion that the cost of steel covers more than 25% (twenty five) of total construction cost. This only indicates that a proper corrosion management is very much in need to protect the asset which are due to deteriorate as time passes by.

Further interviews with the respondent revealed that the price of steel have rose to approximately RM 4000 per tonne. Therefore the cost of steel involved in construction industry has risen sharply due to the increase in price.

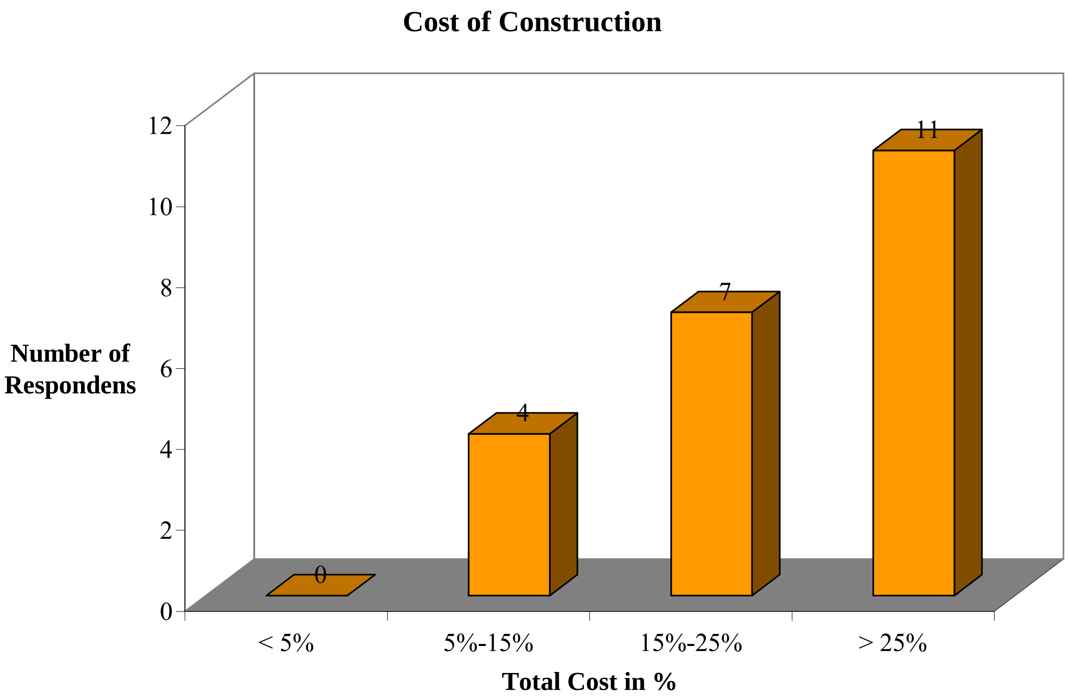

Figure 4.4 Cost of Steel in construction

4.6 Corrosion Prevention Methods Available

The main objective to include this question is to determine the level of familiarity of the corrosion prevention methods available among the respondents. A total of 4 (four) available methods were listed in the questionnaire namely design for durability, concrete technology, surface treatment and corrosion resistant rebars.

Selections on methods of corrosion prevention are abstracted from literature reviews on books and journals. Respondents are expected to fill the question based on their level of familiarity on the methods listed. However, respondents are encouraged to note any other corrosion prevention method available in the practice that was not listed.

The result from the questionnaire has been compiled as shown in Table 4.1. The results apparently reflect the common understanding of professional in the construction industry on the matter regarding corrosion prevention methods.

Table 4.1 Level of familiarity of corrosion prevention methods.

Types of Prevention Methods	Frequency					Average
	1	2	3	4	5	
(a) Design for durability	15	2	2	3	-	1.68
(b) Concrete Technology	9	4	6	3	-	2.14
(c) Surface Treatment	12	3	4	3	-	1.91
(d) Corrosion Resistant Rebar	-	8	7	5	2	3.05

(1 = Very familiar, 2 = Familiar, 3 = Moderately familiar,
4 = Less familiar, 5 = Not familiar)

The results were then interpreted into graphical presentation as shown in Figure 4.5 for easier understanding.

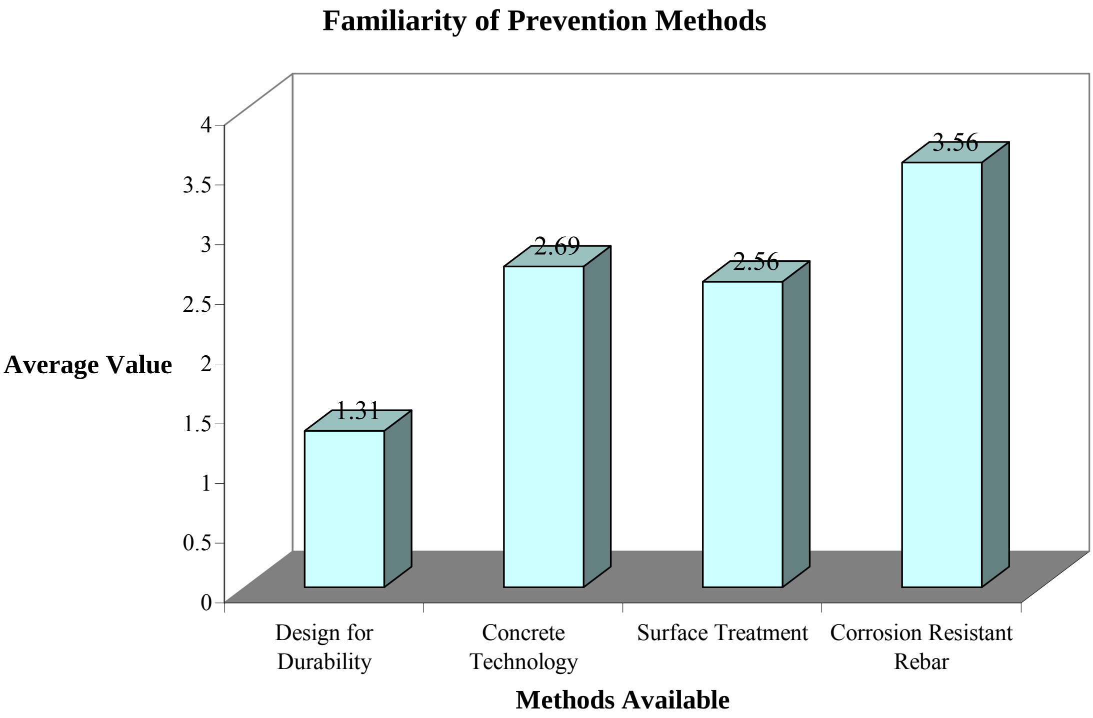

Figure 4.5 Level of familiarity of corrosion prevention methods.

From the analysis, it shows that the “design for durability” method is the most commonly applied method with a average of 1.31. The average value was conducted using the Average Index method as discussed in Chapter III.

Average value for “Concrete Technology” method was 2.69 which is higher than surface treatment (2.56). The result indicates that this method is not popular in the application of corrosion prevention. Further interviews with the respondents revealed that additives needed to produce corrosion resistant are relatively expensive.

Corrosion-Resistant Rebar method has a average value of only 3.56. This was an expected value for “Corrosion-Resistant Rebar” as literature reviews revealed that this method is only common in advanced country. Furthermore, the application of such method is only on very critical structure such as nuclear container to prevent any leakage due to spalling of concrete result from corrosion of reinforcement bars.

Among other methods mentioned by respondent was by applying a layer of bitumen on top of the lean concrete before casting of structural members. Bitumen was produced in the form of a dry sheet that is able to be spread across a large area. It was understood that bitumen is impermeable, therefore it provide the necessary protection against the penetration of moisture to initiate the process of corrosion.

4.7 Frequency of Applying Corrosion Prevention Method

Purpose to include this question in the questionnaire was to determine the common corrosion prevention method applied in Malaysia construction industry. A total of 4 (four) available methods were listed in the questionnaire namely design for durability, concrete technology, surface treatment and corrosion resistant rebars.

Selections on methods of corrosion prevention are abstracted from literature reviews on books and journals. The result from the questionnaire has been compiled as shown in Table 4.2. The average value was calculated using the Average Index method as discussed in Chapter III.

Table 4.2 Frequency of applying the following prevention methods.

Types of Prevention Methods	Frequency					Average
	1	2	3	4	5	
(a) Design of Durability	16	2	4	-	-	1.45
(b) Concrete Technology	7	5	8	2	-	2.23
(c) Surface Treatment	8	4	6	4	-	2.27
(d) Corrosion Resistant Rebar	-	2	4	8	7	3.77

(1 = Very frequent, 2 = Frequent, 3 = Moderate frequent,
4 = Less frequent, 5 = Not frequent)

Results collected were then represented in a graphical form for easier understanding as illustrated in Figure 4.6.

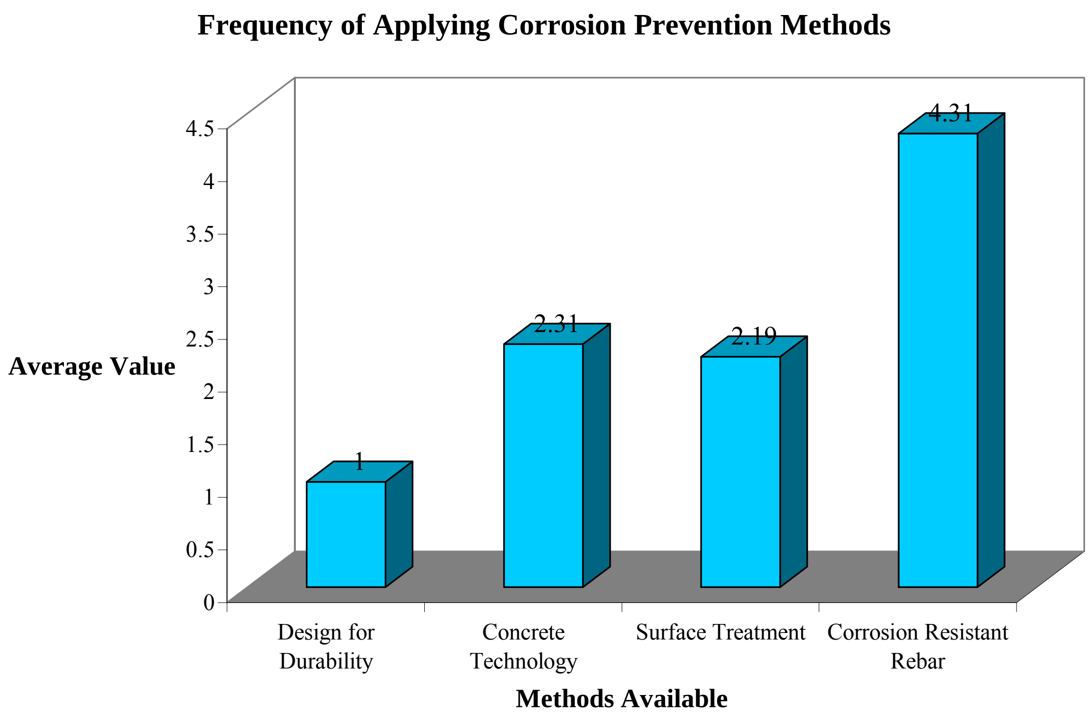

Figure 4.6 Frequency of applying corrosion prevention methods

Findings from the questionnaire revealed that there is certain pattern in the answer from the correspondent particularly for the "design for durability" method and "surface treatment" method. Large portions of the result for "design for durability" were contributed by respondent who are involved in consultancy firm. This is mainly because the standard code for reinforced concrete design in Malaysia requires consultant to take into consideration the concrete cover thickness of all structural members. Apparently thicker concrete cover would prolong the penetration rate of corrosive element into the embedded steel.

The average value of 2.19 for the "surface treatment" method were mostly contributed by respondent working as contractors as it is a usual practice in construction field to treat the surface of concrete with a layer of impermeable material such as bitumen special coatings to prevent the ingress the corrosive elements. Interviews with contractor also revealed that it is a common practice to indicate the application of impermeable coatings on the surface of the concrete by the clients or developers.

The average value of 4.31 for applying corrosion resistant rebar is expected since it is not common for local engineers to design or construct structures that require great strength and durability such as nuclear container.

4.8 Corrosion Repair Method Available

The question was conducted to determine the level of familiarity of the available corrosion repair methods among the professionals in the country's construction industry. The respond received would be able to provide some rough indication on the level of awareness towards corrosion related problems. A total of 4 (four) available methods were listed in the questionnaire namely patch repair method, cathodic protection, cathodic prevention, chloride removal and re-alkalization.

The available methods were abstracted from the literature reviews through books and journals. However, these methods are not exhaustive as respondents were also encouraged to enclose any other available repair methods that are not listed in the questionnaire. This would provide further understanding of the methods being practiced in the industry.

Feedback from the questionnaire where presented in a statistical way as illustrated in Table 4.3.

Table 4.3 Level of familiarity of corrosion repair methods

Types of Corrosion Repair Methods	Frequency					Average
	1	2	3	4	5	
(a) Patch Repair	16	3	2	1	-	1.45
(b) Cathodic Protection	4	5	7	2	4	2.86
(c) Cathodic Prevention	-	3	2	6	11	4.14
(d) Chloride Removal	1	6	4	5	6	3.41
(e) Realkalization	-	-	6	9	7	4.05

(1 = Very familiar, 2 = Familiar, 3 = Moderately familiar,
4 = Less familiar, 5 = Not familiar)

The collected results were then presented in a graphical form as shown in Figure 4.7.

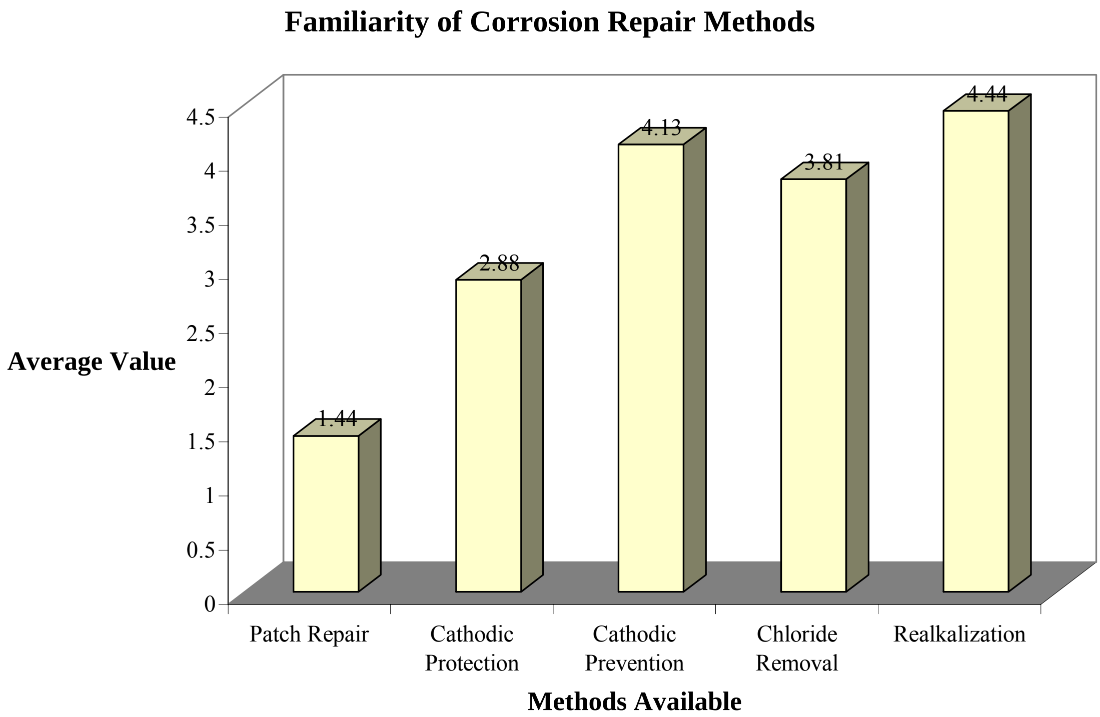

Figure 4.7 Familiarity of corrosion repair method.

Judging from the graph, it is shown that “patch repair” method appeared to be more commonly known among professional compared to other available methods. “Patch Repair” recorded an average of 1.44.

As expected, the average for other methods such as “cathodic protection”, “cathodic prevention”, “chloride removal” and “re-alkalization” are relatively high as compared to “patch repair” method. This is partly due to low awareness of other advanced electrochemical repair technique among the respondents.

Cathodic protection method came in second with an average of 2.88 while chloride removal method came in third with an average of 3.81. Cathodic prevention and re-alkalization has an average of 4.13 and 4.44 respectively.

It appeared that cathodic protection is more commonly known by contractors as this method has been applied in laying service pipes such as gas and water pipes. However, it is noted that this method was rarely applied for structural members of a buildings.

4.9 Frequency of Applying Corrosion Repair Methods

The feedback from this question would reflect the general trend of corrosion repair method being practiced in the country. A total of 4 (four) available methods were listed in the questionnaire namely patch repair method, cathodic protection, cathodic prevention, chloride removal and re-alkalization. The outcomes for the question were presented in a statistical way as illustrated in Table 4.4.

Table 4.4 Frequency of applying the following repair methods.

Types of Corrosion Repair Methods	Frequency					Average
	1	2	3	4	5	
(a) Patch Repair	9	4	6	3	-	2.14
(b) Cathodic Protection	-	1	12	6	3	3.50
(c) Cathodic Prevention	-	1	9	9	3	3.64
(d) Chloride Removal	-	-	10	8	4	3.72
(e) Realkalization	-	-	9	5	8	3.95

(1 = Very frequent, 2 = Frequent, 3 = Moderate frequent,
4 = Less frequent, 5 = Not frequent)

The results were then represented in a graphical form for easier understanding as shown in Figure 4.8.

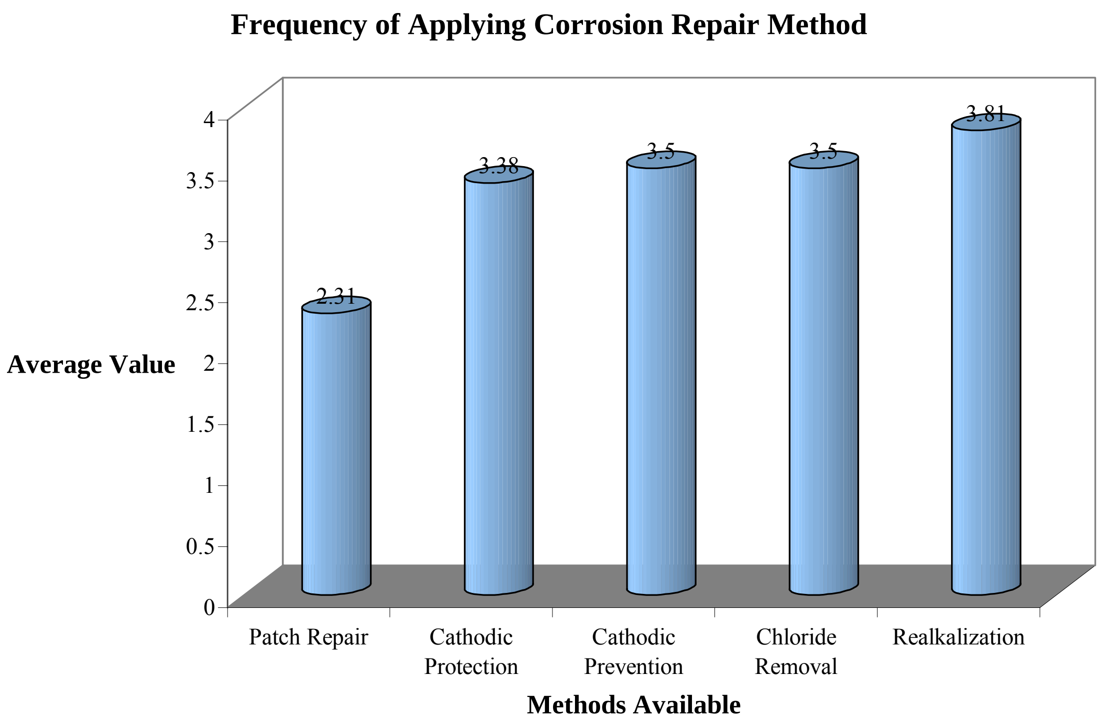

Figure 4.8 Frequency of applying corrosion repair method.

"Patch repair method" has an average score of 2.31. From the result, it is obvious that the patch repair method were the most commonly applied alternatives as compared to others. This is understandably so as this method requires less technical knowledge and the effect of the repair can be seen almost immediately. However, the major drawback of the method is that it does not provide permanent protection to the structure. The problem of corrosion cannot be curbed if the structure is exposed to corrosive environment after the repair.

"Cathodic protection method" was second behind "Patch repair method" with an average of 3.38. However, it was noted by the respondents that such method is more commonly used by contractors for the purpose of protecting service pipes laid underground as compared to protecting steel in reinforced structures.

Other methods such as "cathodic prevention", "chloride removal" and "re-alkalization" merely have a score of 3.50 and 3.81 respectively.

4.10 Conclusion

This indicates that construction industry in Malaysia still lacks the expertise in treating corrosion for steel reinforced structures. The outcome for this questions reflected that temporary remedy is preferred over long term corrosion protection.

CHAPTER V

CASE STUDY

Project : Concrete Repair and Structural Strengthening Works for R.C Approach From Dolphin C to Dolphin D at Quay 2 & 3.

Client : Malaysia Shipyard & Engineering Sdn. Bhd. (MSE)

Contractor : Sinct-Lab Sdn. Bhd

5.1 Introduction

A case study has been carried out on a concrete repair of a shipping yard that was corroded after approximately 15 years of service life. The client involved in the re-construction work is Malaysia Marine and Heavy Engineering Sdn. Bhd. (MMHE) or previously better known as Malaysia Shipyard & Engineering Sdn. Bhd. (MSE). The contractor engaged for the repair work of the corroded shipping dock was Sinct-Lab Sdn. Bhd. Figure 5.1 shows the view of the deck and steel piling of the structure.

Figure 5.1 View of the deck and steel piling

Due to vast experience of Sinct-Lab Sdn. Bhd. in repairing structures, they were nominated as the main contractor for the repair work of Deck Dolphin C to Dolphin D at Quay 2 & Quay 3. Subsequently, they awarded the contract and the work of rehabilitations begins commencement on February 2004.

At that point, Sinct-Lab has a few alternatives in order to repair the docks which were severely corroded due to lack of protective measures taken during construction and also due to daily exposure to corrosive environment. Rate of corrosion increased when tide is high. Continuing ingression of corrosive agents such as chloride from seawater has prompted Sint-Lab to come out with an alternative which will provide long term protection.

However, before deciding on the methods to be applied, a conceptual and feasibility studies has been carried out.

5.2 Visual Aspects

The deck can be divided into 2 major parts namely the deck and the piles. The decks consist of a 1.5m x 0.3 m (T) slab with a length stretching to 17.0m. The slabs are supported by a combination of universal I-beam with the pile spacing at every 7.5 m.

Visual inspection indicates that the member of beams and slab were severely corroded with traces of brownish tracks visible along the line of reinforcements as shown in Figure 5.2. Concrete was seen spalling off the deck which was believed to be caused by expansion of the steel due to the rust produced by the process of corrosion. Figure 5.3 illustrate the seriousness of concrete spalling due to corroded rebars. However, the degree of corrosion could not be determined until the concrete cover of the reinforcement is hacked.

Figure 5.2 Tracks of corrosion along the reinforcement arrangement.

Figure 5.3 Concrete cover spalling off from corroded rebars.

5.2.1 Cause of Corrosion of the Deck

Attack of concrete by seawater can be of various types: superficial erosion caused by waves of tides, swelling caused by crystallization of salts, chemical attack by salt dissolved in the water. The most critical part of the structure are the tidal and splash zones which happened to be the deck. Cyclic drying and capillary suction occur in the concrete just above sea level, dissolved salts were carried by water into the concrete. Evaporation of the salts caused these salt to crystallize in the pores, producing stresses that can cause microcracking which explains the reason of concrete spalling off the structure. Concrete structures which are near but not exposed to seawater suffer similar fate through wind depositing salt aerosols. Figure 5.4 below shows the disintegration of concrete from the beams.

Figure 5.4 Concrete cover was seen disintegrated from beams.

5.3 Underwater Inspection

An underwater inspection was conducted to further understand the extend of the problem occurred due to corrosion. Figure 5.5 illustrates the process of underwater inspection.

Figure 5.5 Underwater inspection

5.3.1 Causes of Corrosion on Steel Piling

Corrosion occurs because of small physical and/or chemical differences present in metals or in the environment. The differential conditions in the metal arise from minor impurities, local variations, surface scratches and abrasion, breaks in the mill scale, locked in thermal stresses, stray current, galvanic couples and bacterial activity, to cite a few examples. Differential environmental condition may arise from changes in amounts of dissolved oxygen varying with the depth of immersion, local fluctuation of velocity or non-uniform salt concentration because of surface pollution. Such condition creates local dissimilar sites on the surface of the metal that interact electrochemically.

5.3.2 Corrosion Mechanism of Steel in Seawater

On steel piling in seawater, the more chemically active surface areas (anodes) are metallically coupled through the piling itself to the less chemically active surface areas (cathodes) resulting in a flow of electricity and corrosion of the anodic areas. General surface roughening occurs when these local anodic and cathodic areas continually shift about randomly during the corrosion process. Sometimes these active local areas do not shift position end, therefore, the metal suffers localized attack and pitting occurs. In general, the depth of pitting is related to the ratio of the anodic sites to the area of cathodic site in contact with the electrolyte (seawater), the smaller the anode area relative to the cathode area, the deeper the pitting.

5.3.3 Zones of Corrosion of Steel Piles

Examination of corroded marine piles reveals several distinct areas of attack. It is convenient to dive these areas into five zones, each having a characteristic corrosion rate as shown in Figure 5.6 below.

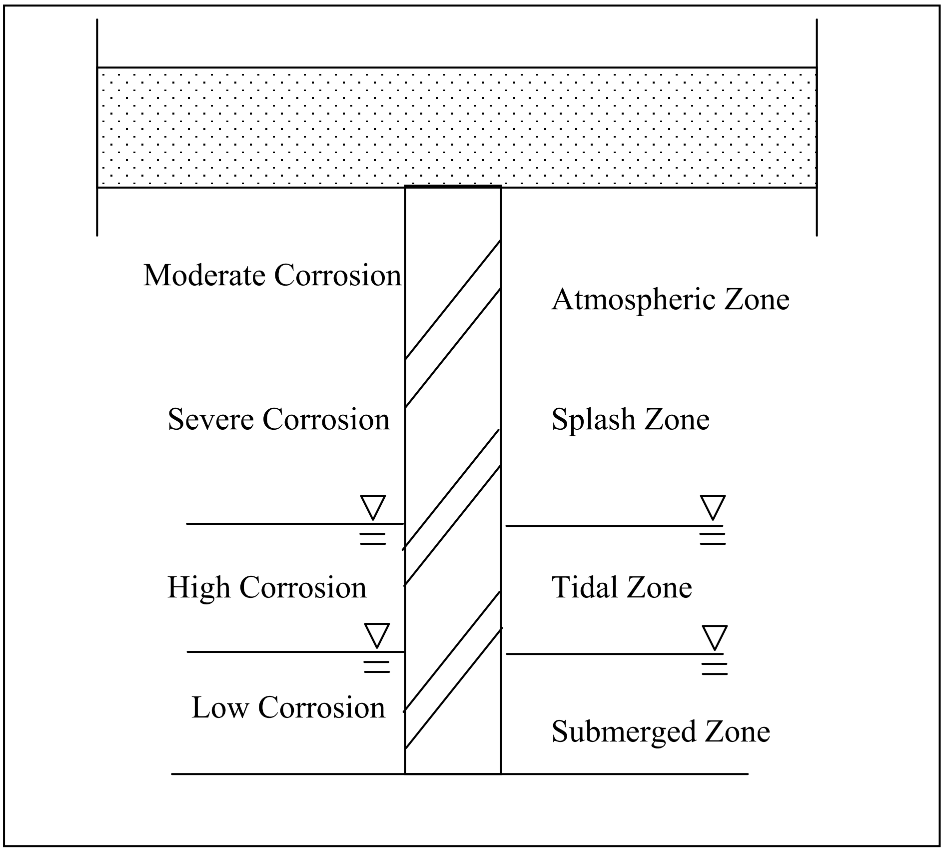

Figure 5.6 Typical corrosion regions of a steel pile in marine environment.

5.3.3.1 Atmospheric Zone

This is the area at the top of the piles that is continuously exposed to the atmosphere above the splash zone. This area is accessible for maintenance. Figure 5.7 illustrate corrosion taking place at the atmospheric zone of the steel pile.

Figure 5.7 Corrosion at atmospheric zone

5.3.3.2 Splash Zone

This is the area from the mean high water level upward to the bottom of the atmospheric zone. In this area moisture droplets and continuous water films are maintained on the pile surfaces exposed to the atmosphere. These areas are accessible for maintenance, with some inconvenience, at low tide. Figure 5.8 illustrate corrosion taking place at the splash zone of the steel pile.

Figure 5.8 Corrosion at splash zone

5.3.3.3 Tidal Zone

This is the area between mean low water level and high water level. This zone is subject to alternate periodic immersion owing to tide changes and is accessible for maintenance at low tide with difficulty. Figure 5.9 shows that the tidal zone are moderately corroded as there is no sign of living organism on the steel pile.

Figure 5.9 Corrosion at tidal zone.

5.3.3.4 Submerged Zone

This is the area of the piles that is always submerged extending from the mud line upward to mean low water level. (This zone does not exist in those locations where the mud line is above the mean low water level.) Generally, permanent submersion is less severe than tidal or splash zone exposure. Figure 5.10 suggests that the zone is in good condition as large portion of the pile are covered with living clamps. It was understood that organism would not be able to survive with the existence of toxic from corrosion.

This area is not readily accessible for maintenance without recourse to cofferdam techniques or specialized underwater painting techniques.

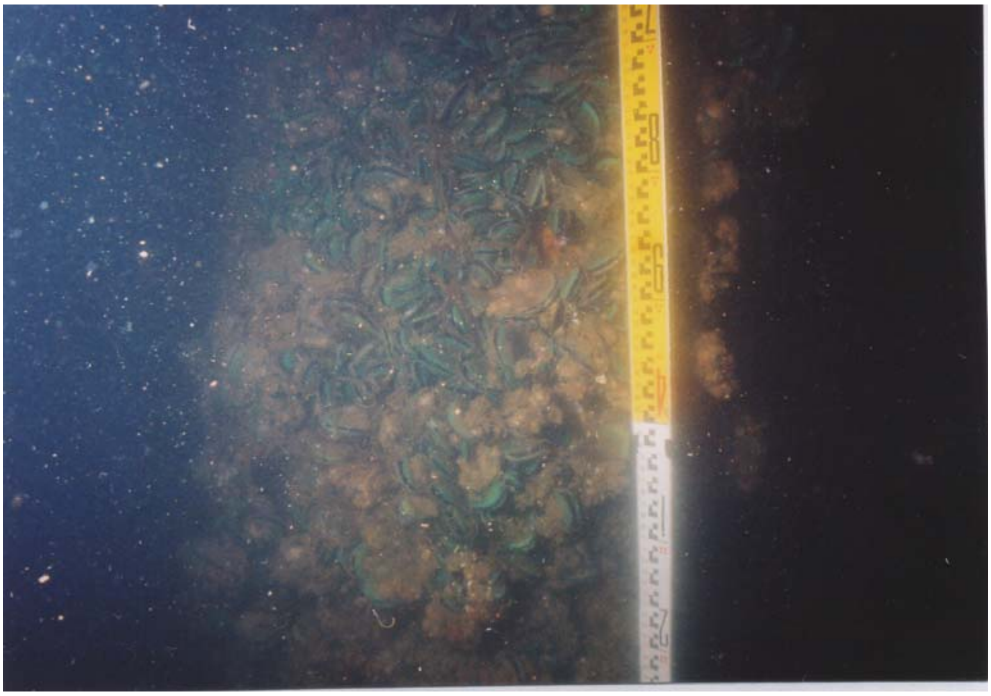

Figure 5.10 Corrosion at submerged zone

5.4 Visual Inspection on 19 numbers of Steel Pile With Diameter 600 mm Between Dolphin C and Dolphin D

Before a visual inspection is carried out, primary data was required to plan for a systematic visual inspection. Those data being obtained included the Tide Table from Maritime Department and the layout plan of the steel pipe pile between Dolphin C and Dolphin D.

From the tide table for Pasir Gudang area issued by maritime department in the year 2004, the highest tide of the year would fall on 17 October 2004 at 1.05am with level 3.5m, while the lowest tide of the year would fall on 3 July 2004 at 5.13 am with level 0m.

The statistic of seawater level was important as suitable condition is needed to obtain a good underwater visibility. Factors that influence the underwater visibility include the exposure of the sun light and the particles in the water. For Pasir Gudang area, a bright sun light usually could be obtained in the morning, from 7 am to 12 am. On the other hand, the particles in the water could be reduced during the high tide when clean water rush into the shore are. Base on the tide table from the Maritime Department, the visual inspection was planned to be carried out on 20 March 2004 where the tide would rised from 4.30am to 11.00am. As the situation fulfills both the above criteria, the underwater visual inspection was carried out as planned with the underwater visibility around 1m at the depth of 5m.

Knowing that the tidal zone suffers the highest rate of corrosion, corrosion mapping would be concentrated on the tidal zone which around 3.5 m below the sophist of the R.C approached deck.

The inspection of the steel pipe piles was carried out in two phases, surface inspection and submerges inspection. The surface inspection was carried out at 7.30 am on 20 March 2004. The tide level on that moment was 1.8m below the RC beam for the approach deck. Photographs were taken for the 19 steel pipe piles to be inspected. The submerge inspection was carried out at 9.00 am on the same day, the inspection started from steel pipe pile A1. Four photographs from various angle and depth were taken for each steel pipe pile.

5.5 Conclusion of The Visual Inspection.

Based on the visual inspection, the deck of the structure clearly indicates severed corrosion activity took place. As for the steel piling, some part of the steel pipe pile is covered with shells and various types of corals. Overall, the steel pipe piles between Dolphin C and Dolphin D are in moderate condition. A few areas in the tidal zone suffered corrosion which was indicated in brown color. However, some part of the steel pile which were covered with other organism were found not to be seriously corroded as micro organism such as coral and shells could hardly survive on the severely corroded area because iron rust is toxic to them.

As a conclusion, a routine maintenance work is needed to be carried out for those steel pipe piles in order to make sure the effectiveness as a load transfer structure to the hard strata. However, as for the deck, the reinforcements are needed to be replaced as the strength of the steel would reduce significantly in near future. Protective measures were also required to be introduced to prevent the ingress of corrosive elements and thus prolong the service life of the structure.

5.6 Cost of Concrete Repair and Structural Strengthening Works.

No.	Description	Qty	Rate (RM)	Amount (RM)
1.	**<u>Preliminaries</u>** To mobilize and provide insurance coverage, set up at site and preparation works and safety equipment.	1 job	Lump sum	4,800.00
2.	**<u>Staging For Access And Boat Inspection Services.</u>** To provide working staging, plate form and wiring to secure necessary works. Supply include one fibre glass boat service for inspection purpose.	1 job	Lump sum	19,500.00
3.	**<u>Hacking and Remove Spall-Concrete</u>** To hack away spall concrete and remove severely corroded steel bar from beam soffit prepare surface of concrete for repair purpose	190 m^2	65.00 /m^2	12,350.00
4.	**<u>Clean Concrete Surface.</u>** To apply high pressure water jet with only fresh water to remove concrete dust, salt residue and rusty stains from concrete surface. (Note : Exclude staging)	190 m^2	6.50 /m^2	1,235.00
5.	**<u>Anti-Corrosion Impregnator To RC Structure.</u>** To supply and apply anti-corrosion impregnator, Sika Ferrogard 903, onto concrete surface. All in accordance with manufacturer's specification.	190 m^2	38.00 /m^2	7,220.00
6.	**<u>Reinforcement Steel</u>** To replace corroded steel bar with new reinforcement bar. a) Y10 b) Y16 c) Y25	 850 kg 210 kg 5900 kg	 3.50 3.50 3.50	 2,975.00 735.00 20,650.00
	Balance b/f :			**69,465.00**

No.	Description	Qty	Rate (RM)	Amount (RM)
	Balance c/f :			**69,465.00**
7.	**<u>Anticorrosion Coating To Steel Bar.</u>** To supply and apply two (2) coats of anti- corrosion coating, sikatop Armatec 110 Epocem to newly placed steel bar. All in accordance with manufacturer's specification.	240 m^2	38.00 /m^2	9,120.00
8.	**<u>Rebar For Link Reinforcement.</u>** To supply chemical and set Y10 link reinforcement by starter bar method using Sika Power Fix 1 epoxy set chemical. All in accordance with manufacturer's specification.	2,039 nos	12.00 /no	24,468.00
9.	**<u>Formwork Pressure Grouting.</u>** To supply material and labour for formwork pressure grouting with high strength grout, Sika Grout 215. All in accordance with manufacturer's specification.	190 m^2	285.00 /m^2	54,150.00
10.	**<u>Hand Patch Repair Mortar.</u>** To supply material and labour for hand patch repair mortar, Sika Monotop R to small area of soffit. All in accordance with manufacturer's specification.	20 m^2	270.00 /m^2	5,400.00
11.	**<u>CFRP Reinforcement To Beam.</u>** To supply and apply CFRP Strip to soffit of RC beam after repaired as an additional safety element to deck system. All in accordance to manufacturer's specification.	165.60 m	350.00 /m	57,960.00
12.	**<u>Clean Concrete Surface For Surface Coating.</u>** To apply high pressure water jet with only fresh water to remove concrete dust, Salt residue and rusty stains from concrete surface.	724 m^2	3.50 /m^2	2,534.00
	Balance b/f :			**223,097.00**

No.	Description	Qty	Rate (RM)	Amount (RM)
	Balance c/f :			**223,097.00**
13.	**Protective Coating To Concrete Surface.** To supply and apply Sikagard 700S as a primer to concrete surface and complete with 2 coats of Sikagard 670W, acrylic based fast cure epoxy coating to concrete surface. All in accordance with manufacturer's specification.	724 m^2	65.00 /m^2	47,060.00
14.	**Anti-corrosion Impregnator To RC Structure** To supply and apply anti-corrosion impregnator, Sika Ferrogard 903, onto concrete surface. All in accordance with manufacturer's specifications.	724 m^2	38.00 /m^2	27,512.00
15.	**Protective Coating To Steel Pile Jacket** To supply and apply 2coats of high performance anti-corrosion coating, Sika Internol Poxitar F, heavy duty coal tar epoxy layer for steel surface. Works inclusive of surface preparation with mechanical wirebrush.	161 m^2	95.00 / m^2	15,295.00
16.	**Jacketing To Existing Marine File.** To supply and construct ?600mm -loc jacketing with underwater grout to existing marine pile. Works inclusive of additional steel bar and links inside rib-loc jacket.	95 m	350.00 /m	33,250.00
17.	**12months Maintenance Period** To provide all necessary material and labour, equipments for maintenance of RC structure structure during the maintenance period. Works inclusive of regular inspection to jetty structure. (Note : Monthly inspection schedule)	1 job	Lump sum	2,500.00
	Total :			**348,714.00**

The Bills of Quantities above illustrated a typical quotation of cost for the rehabilitation of concrete structure involved in the project. It was clearly shown that cost to repair is high due to the complexity of the work that was carried out.

Of the total amount of RM 348,714.00, a relatively big portion was contributed to the process of carrying out feasibility studies, preparation of concrete repair and also the replacement of reinforcement steel bar.

It can be calculated that approximately 6.0% of the total cost goes to preliminaries and inspection. Preliminaries include the insurances coverage as well as the mobilization of necessary plant and safety equipments. However, of the 6.0%, most of the cost was spent on conducting underwater inspection as specially trained diver was engaged to perform the duty.

Work for the preparation of concrete repair such hacking off spalling concrete and cleaning concrete surface cost around RM 13,585.00. The cost of these activities was relatively low as it does not require the engagement of skilled workers to deliver the job.

Meanwhile, the cost of replacing reinforcement bar of the structure contributed 15.0 % of the total cost and the cost of applying formwork pressure grouting, too, cost approximately the same figure of total cost.

All the items mentioned above are avoidable and unnecessary if early precaution and prevention measures were taken into consideration during the construction of the structures. These are redundant activities that could be avoided if sufficient protection was provided to the reinforcement bar during and before the construction. The redundancy was quoted to be approximately 42.0 % of RM 348,714.00 which work out a total of RM 146,460.00. In other word, RM 146,460.00 could have been saved if prevention measures were taken back then.

5.7 Comparison of Cost: Then and Present

As mentioned earlier, a total of approximately RM 146,460.00 could have been saved from the client if necessary measures were taken and was carefully designed. However, the value of money at present is different from time to time. In a lay man’s term, the value of money is subject to depreciation. The value of one Ringgit (RM1.00) now should be less ten years back. This provides an interesting discussion of how much the client could actually have saved if he had chosen any form of protection when the structure was first constructed.

As mentioned in Chapter II, there is an economic approach to calculate the past, present, future as well as annual worth of currency. The comparison of value of money can be applied for the purpose of determining the actual cost that the client would have saved back when the design of the deck was at it’s conceptual stage.

5.8 Calculation of Present and Future Value of Cost of Corrosion

One of the criteria needed to calculate the value of the project is the age of the structure. The age of the structure being discussed is expected to be around 10-15 years old. For the purpose of calculation and being conservative, the age of the structure is assumed to be 12 years old. The exact age of the structure being repaired is unknown as the client did not disclose any form of data that could suggest the service life of the deck. However, the prediction of age was confirmed by engineers from the contractor firm as test result of concrete indicates the structure to be around a decade old.

Another important information required for the calculation is the rate of interest of the Ringgit Malaysia (RM) currency. Rate of interest varies from time to time depending on the performance of the market as well as the economic power and potential of the country. Therefore, the exact figure for the average rate of interest through the lifetime of the structure is rather subjective. However, a check with Bank Negara indicates that rate of interest for the past 8 years were stable ranging from 4.0 % to 6.0 %. Therefore, for the purpose this paper, the interest was set at the average rate of 8.50 %.

The formula applied in the calculation for the project is a single amount method. The formula for the method is as shown below:

$$(\ P/F,\ i,\ n\ ) = \frac{1}{(1+i)^\wedge n} \qquad , \qquad P = F\ (\ P/F,\ i,\ n\ )$$

where, P = Present Value

F = Future Value

i = Rate of Interest

n = number of years

Assumed, P = unknown

F = RM 146,460.00

i = 8.50 %

n = 12 years

Therefore, P = RM 146,460.00 x $\frac{1}{(1+5.0\%)^\wedge 12}$

= RM 146,460.00 x 0.557

= <u>**RM 81,554.41**</u>

5.9 Cost Benefit Ratio

Cost-benefit ratio for a project can be divided into two criteria, namely direct and indirect benefit. Direct benefit refers to measurable benefit that people would enjoy from the launching of the project. Such benefits include extended service life of a structure after adequate protection was given. Indirect benefit refers to immeasurable benefit such as increase of efficiency of the structure after repair.

The formula and calculation of cost-benefit ratio for the purpose of this study is as shown in below:

Conventional Method:

$$B/C = \frac{Benefit - Disbenefit}{Cost} = \frac{B - D}{C} \qquad \text{or}$$

$$B/C = \frac{PW(benefit)}{PW(total\cos t)} = \frac{PW(B) - PW(D)}{1 - PW(F) + PW\cos(O\,\&\,M)}$$

Modified Method:

$$B/C = \frac{Benefit - Disbenefit - O\,\&\,M}{InitialCost - F} = \frac{B - D - O\,\&\,M}{I - F} \qquad \text{or}$$

$$B/C = \frac{PW(Benefit) - PW(Disbenefit) - PW(O\,\&\,M)}{PW(total\cos t)}$$

$$= \frac{PW(B) - PW(D) - PW(O\,\&\,M)}{I - PW(F)}$$

Assuming that the extension of time needed to implement corrosion prevention method is 5 days. Each day of the delay would cost the client to generate a loss of RM10, 000.00. Another assumption needed for the calculation is that the repaired structure would enjoy an extension of 15 years of service life. It was quoted by the contractor that annual maintenance on the repaired structure would cost RM2,500.00. Since the rate of interest remain unchanged, present value of the repair work could be applied without having converted to annual or future value. Therefore, Conventional Method:

$$B/C = \frac{PW(benefit)}{PW(total\cos t)} = \frac{PW(B) - PW(D)}{I - PW(F) + PW\cos(O \& M)}$$

$$= \frac{RM\,348{,}714.00 - RM\,50{,}000.00}{RM\,202{,}254.00 + RM\,37{,}500.00}$$

= 1.25 > 1.0

Modified Method:

$$B/C = \frac{PW(Benefit) - PW(Disbenefit) - PW(O \& M)}{PW(total\cos t)}$$

$$= \frac{RM\,348{,}714.00 - RM\,50{,}000.00 - RM\,37{,}500.0}{RM\,202{,}254.00}$$

= 1.29 > 1.0

From the calculation of cost-benefit ratio, it provides direct evidence that it is more feasible to adopt an effective corrosion management program in the early stage of construction.

5.10 Conclusion of Cost Calculation

It was calculated that RM 81,554.41 could have been saved if the client opted to have a proper corrosion protection system designed before construction of the structure.

Figures are the most effective way to measure the importance of a proper corrosion management system. Past and present value of money spent for repairing of concrete structure caused by corrosion provides a scaling factor that can be used to compare the significance of corrosion management. In other word, a proper corrosion management system can be considered as a property management.

CHAPTER VI

CONCLUSION AND SUGGESTIONS

6.1 Introduction

Most of the structures around us are exposed to corroding environment in their day to day existence. Initially, this exposure would not have any detrimental effect on performance. However, over the time, signs of distress such as cracking and spalling start to appear. Effect of corrosion proved to be a serious issue and tend to threaten the service life of the structure. In other word, the issue of corrosion can be seen as a threat to existing property.

Having said so, it is only reasonable to develop a management program that would recognize the degree of the problem from conceptual or design stage.

This study consists of four (4) major objectives as mentioned in Chapter 1. Generally, all four (4) objectives were successfully achieved in accordance to the requirement of this study.

Average index method and statistical method have been applied for the purpose of analyzing the collected data from the distributed questionnaires. Other than that, a case study and an interview have been conducted in order to obtain further understanding of the degree of corrosion faced in construction industry.

6.2 Conclusion

6.2.1 Corrosion Management Program

Corrosion is a fact of life in operation. If left unmanaged, corrosion can cause premature structure defect and thus leading to unnecessarily high maintenance cost and safety problem. So as to speak, owner of both private and public structure are faced with rising cost to maintain their assets. Worried owners recognize the need to protect their investment that can economically extend the service life of their property.

Typically, corrosion management can be divided into three (3) major phases [11]. Phase 1 of the program is the programmatic assessment of the project. This phase is the planning stage for a corrosion management program to take place. It initiates the program to be implemented on structures that are found to be under the threat of corrosion. For the planning stage, three (3) main requirements are sought, namely the strategy, budget and schedule needed to overcome the problem arised from corrosion of reinforcement. This is seen as an important part for an effective management program as feasibility studies are normally conducted to determine the serviceability of the structure after treatment.

Phase 2 of the program involves physical assessment and actual remediation. Inspections for severity of corrosion are conducted in this phase to determine what strategy or methods are most suitable to be applied. Development of corrosion control strategy would present more option to the management program. Remedial work would be carried out once the proper strategy has been recognized.

Phase 3 of the program mainly deals with future monitoring of the repaired structure. Currently and historically, most of the corrosion control programs are driven by response to incident or urgent need, rather than systematically identifying and managing the existing resources. This can be overcome by implementing internal or external monitoring system using current technology practiced in oil and gas industries. One such device that could be installed are CorrosoMeter, CorroTemp and Corrater probes. The overall flowchart for an effective corrosion management program is as illustrated in Figure 6.1

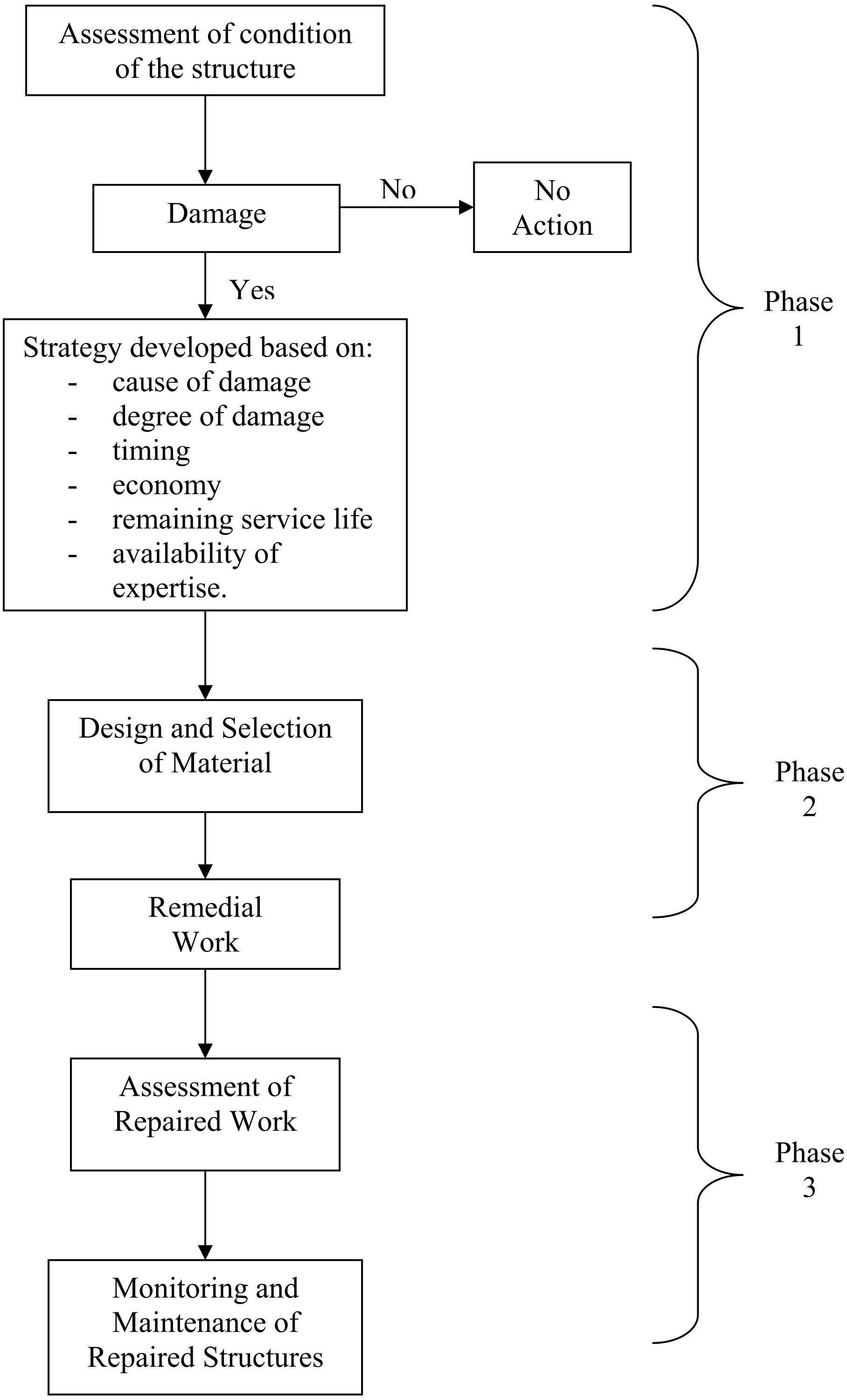

Figure 6.1 Typical Corrosion Management Program

6.2.2 Methods of Corrosion Prevention

Among the more common methods available for preventing corrosion are as follow:

1. Design for Durability
2. Concrete Technology for Corrosion Prevention
3. Surface Treatments
4. Corrosion-resistant Reinforcement.

6.2.2.1 Design for Durability

Prevention of reinforcement corrosion and other types of deterioration begins in the design phase. A properly designed concrete structure would probably possess the characteristic required so that corrosion of reinforcement is not likely to initiate throughout the service life.

Two major design approaches that would affect the durability of concrete structure are design of concrete quality and design of cover thickness. Under the influence of different corrosive environment, both of the design approach must be adequate to provide sufficient protection from the ingress of corrosive agents. Generally, it can be summarize that a concrete of very high grade and thick cover are more durable as such concrete are less porous and permeable due to denser content of cement.

6.2.2.2 Concrete Technology

For a concrete structure that would endure in mild aggressiveness environment, the strength requirements for concrete are in the usual range whereby Ordinary Portland Cement (OPC) would be suitable. However, such cement could not provide the necessary protection when the structure is exposed to a more aggressive environment.

Having said so, admixtures such as pozzolana or blast furnace slag could be incorporated into normal cement blend as such chemical composition reduce the rate of development of heat of hydration and are able to produce a denser cement paste.

Such additives are especially effective to prevent corrosion for certain application such as those requiring higher resistance to sulfate attack.

6.2.2.3 Surface Treatment

Surface treatments are applied to new structures as a preventative measure from corrosion. However, it can also be applied to repaired structures in hoping to improve the service life of the repairs.

A wide range of materials are used for the purpose of surface treatment. Among the more common ones are those of polymeric and cementitious. However, all materials share a common objective which is to make the concrete cover zone less permeable to aggressive substances.

It can be considered as a common practice in local construction industry for applying surface treatment in order to curb the problem arising from corrosion.

Impermeable materials are normally laid right after the lean concrete layer and before the erection of super structure such as ground beam and slab on the ground.

6.2.2.4 Corrosion Resistant Rebar

Generally, rebars used for erection of structures are those made of carbon-steel. These rebars provide adequate strength for load taking structure member. However, it is not meant to endure conditions of high environmental aggressiveness. Such environment requires some modification to the steel. Such modification can be done by spraying a metallic or organic coating on their surface. A modified reinforcement bar is suitable to be used in an aggressive environment or when a long service life is required.

6.3 Cost-Benefit Ratio

As mentioned in the case study conducted in Chapter V, it can be concluded that a huge amount of money could be saved from a proper corrosion management system. Implementation of corrosion management program proved to be beneficial not only to the client but as well as the end-user of the structure. Under certain circumstances, monetary matter for the repair or maintenance work is of minor problem whereas the end-user of the structure would bear the consequences of ceased operation resulting from the work.

An expensive piece of structure constructed without proper corrosion management fits into the saying of “penny wise, pound foolish” perfectly. The so-called De Sitter’s “law of five” can be stated as follows: one dollar spent in getting the structure designed and built correctly is as effective as spending $5 when the structure has been constructed but corrosion has yet to start, $25 when corrosion has started at some points, and $125 when corrosion has become widespread.

6.4 Problems in Corrosion Management

From the collected data and information, the ranking of problems faced in local construction industry regarding to corrosion are as follows:

1. Lack of proper storage area for rebars.
2. Environmental effect.
3. Lack of fund to conduct proper application of corrosion prevention method on rebars.
4. Rebars were already corroded before reaching to site.
5. Lack of supervision on the quality of work.
6. Application of lower grade concrete.
7. Insufficient design of concrete cover
8. Lack of knowledge on proper handling of corroded rebars.

Those mentioned above are the problems faced in local construction industry according to various players of the industry. However, the root cause of the problem was not addressed. It is fair to conclude that it is the lack of awareness that contributed to the arising of those mentioned problems. People in the industry fail to recognize not only the potential danger of corroded structure but also the potential of cost saving if appropriate measures are taken.

6.5 Suggestions

Based on the findings of this study, a few suggestions can be recommended to improve the current scenario.

1. Education. The most effective way to change the mindset of younger generation of engineers is through education. Current syllabus covers only limited area on issues regarding corrosion. Many practicing engineers are unaware of methods available to treat and prevent corrosion from initiating. Courses on the importance of managing corrosion for reinforcement concrete are essential to increase the awareness of professionals. These courses can be conducted by construction governing board and attendance of contractors dealing with critical structures can be made compulsory.

2. Training. Education alone is insufficient to develop an effective corrosion management program. Installation of monitoring gauges such as fiber optic on structures must be taught to contractors as well as owners of both private and public structure. Besides that, installation of corrosion repair system such as cathodic protection system require special expertise. Training courses can be conducted to provide better technical understanding for builders of such structures.

3. Review existing procedures, guidelines and documentations. There is a need to revise, add standards and add sections to the existing guidelines which will address specific requirement for corrosion control. These additions would provide an expanded version of the corrosion control section. These guidelines should be able to specify the appropriate material to be applied to prevent corrosion at the design stage.

4. It is the responsibility of all engineers to update themselves with the latest development of any available corrosion management program. New technology can be learnt and applied in local construction industry.

5. Local governing bodies such as CIDB should provide fund for research and development purpose regarding to corrosion management studies. This could be a form of encouragement for local professionals to conduct necessary research regarding the benefit of such program and the potential of cost saving through it. Nothing much could be achieved without monetary aid from such bodies as it is normally costly to conduct such research.

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APPENDIX

QUESTIONNAIRE

Chew We-sen
4, Jalan Kemajuan 21,
Taman Universiti,
81300 Skudai,
Johor.

Recipient : ____

____

Dear Sir/Madam,

I am a final year student undertaking Master's Degree Program (Construction Management) in the Faculty of Civil Engineering, Universiti Teknologi Malaysia, Skudai. I am currently doing a thesis with the title "**Corrosion Management of Steel Reinforced Concrete**". I am required to conduct a survey to study several general issues concerning the title.

The main objectives of this survey are:

a. To study the corrosion management program.
b. To identify the methods of corrosion prevention.
c. To evaluate the cost-benefit ratio of the management.
d. To identify the problems in corrosion management.

Attached with is the official letter from my faculty in recognition of my status as a student under the faculty.

Your cooperation in answering this questionnaire and duly replying is highly appreciated.

Thank you.

Yours faithfully,

____
(CHEW WE-SEN)
I/C No.: 820121-01-5537

1. Bidang yang diceburi / *Field involved in*

   ☐ Pemaju / Developer

   ☐ Perunding / Consultant

   ☐ Kontraktor / Contractor

   Pengalaman dalam bidang ini / *Experience in your field*: ______ tahun / *years*

2. Jumlah projek perumahan yang pernah dimaju, direkabentuk atau dibina ?
   Total numbers of housing estate project that has been developed, designed or constructed before ?

   ☐ < 5

   ☐ 5-10

   ☐ 10-20

   ☐ > 20

3. Jumlah projek bangunan tinggi yang pernah dimaju, direkabentuk atau dibina?
   Total numbers of high rise project that has been developed, designed or constructed before ?

   ☐ < 5

   ☐ 5-10

   ☐ 10-20

   ☐ >20

4. Jumlah struktur pinggir pantai yang pernah dimaju, direkabentuk atau dibina?
   Total numbers of off shore structure that has been developed, designed or constructed before ?

   ☐ < 5

   ☐ 5-10

   ☐ 10-20

   ☐ >20

5. Secara umumnya, berapakah peratusan kos penggunaan besi tetulang dalam suatu projek berbanding dengan jumlah kos bangunan (tidak termasuk kos tanah)
In general, what is the percentage of the cost of steel used in a project as compared to the total construction cost (not including cost of land) ?

- [ ] < 5%
- [ ] 5%-15%
- [ ] 15%-25%
- [ ] > 25%

6. Untuk setiap jenis anggota struktur berikut, sila nyatakan saiz tetulang besi yang paling kerap digunakan.
For each of the following member of a structure, please state the size of reinforcement bar most frequently used.

	≤T10	T12	T16	T20	≥T25
(a) Tukup cerucuk / *pile cap*	☐	☐	☐	☐	☐
(b) Asas / *Foundation*	☐	☐	☐	☐	☐
(c) Rasuk / *Beam*	☐	☐	☐	☐	☐
(d) Tiang / *Column*	☐	☐	☐	☐	☐
(e) Dinding penahan / *Retaining Wall*	☐	☐	☐	☐	☐
(f) Lantai / *Slab*	☐	☐	☐	☐	☐

Panduan untuk soalan berikut / Guideline for the following questions

> * Note: 1 = Sangat kenal / Very familiar
> 2 = Kenal / Familiar
> 3 = Sederhana kenal / Moderately familiar
> 4 = Kurang kenal / Less familiar
> 5 = Tidak kenal / Not familiar

7. Berpandukan pengalaman dan pengetahuan, apakah tahap pengenalan kaedah pengelakan pengaratan besi tetulang berikut /
Based on experience, what is the level of familiarity of the following corrosion prevention method available for reinforced concrete structure?

	*	1	2	3	4	5
(a) Rekabentuk untuk kekuatan/ *Design for durability*		☐	☐	☐	☐	☐
(b) Teknologi konkrit / *Concrete technology*		☐	☐	☐	☐	☐
(c) Rawatan permukaan / *Surface treatment*		☐	☐	☐	☐	☐
(d) Tetulang tahan karat / *Corrosion-resistant rebar*		☐	☐	☐	☐	☐

8. Sila nyatakan (jika ada) kaedah pengelakan pengaratan tetulang selain daripada yang dinyatakan atas /
   Please state (if any) other corrosion prevention method for reinforced concrete other than the above mentioned methods.

   ____

Panduan untuk soalan berikut / Guideline for the following questions

** Note: 1 = Sangat kerap / Very frequent
2 = Kerap / Frequent
3 = Sederhana kerap / Moderate frequent
4 = Kurang kerap / Less frequent
5 = Tidak kerap / Not frequent

9. Berpandukan pengalaman, apakah kekerapan mengaplikasikan kaedah pengelakan pengaratan tetulang konkrit yang berikut /
   Based on experience, what is the frequency of applying the following corrosion prevention methods for steel reinforced concrete?

	**	1	2	3	4	5
(a) Rekabentuk untuk kekuatan/ *Design for durability*		☐	☐	☐	☐	☐
(b) Teknologi konkrit / *Concrete technology*		☐	☐	☐	☐	☐
(c) Rawatan permukaan / *Surface treatment*		☐	☐	☐	☐	☐

(d) Tetulang tahan karat /
Corrosion-resistant rebar ☐ ☐ ☐ ☐ ☐

Panduan untuk soalan berikut / Guideline for the following questions

* Note: 1 = Sangat kenal / Very familiar
2 = Kenal / Familiar
3 = Sederhana kenal / Moderately familiar
4 = Kurang kenal / Less familiar
5 = Tidak kenal / Not familiar

10. Berpandukan pengalaman dan pengetahuan, apakah tahap pengenalan kaedah memperbaiki pengaratan besi tetulang berikut /
Based on experience, what is the level of familiarity of the following corrosion repair method available for steel reinforced concrete structure?

*	1	2	3	4	5
(a) Patch repair method	☐	☐	☐	☐	☐
(b) Perlindungan katodik / *Cathodic protection*	☐	☐	☐	☐	☐
(c) Pengelakan katodik / *Cathodic prevention*	☐	☐	☐	☐	☐
(d) Pengeluaran klorida / *Chloride removal*	☐	☐	☐	☐	☐
(e) Pengalkalian semula / *Realkalization*	☐	☐	☐	☐	☐

11. Sila nyatakan (jika ada) kaedah memperbaiki pengaratan tetulang selain daripada yang dinyatakan atas /
Please state (if any) other corrosion repair method for reinforced concrete other than the above mentioned methods.

____

Panduan untuk soalan berikut / Guideline for the following questions

** Note: 1 = Sangat kerap / Very frequent
2 = Kerap / Frequent
3 = Sederhana kerap / Moderate frequent
4 = Kurang kerap / Less frequent
5 = Tidak kerap / Not frequent

12. Berpandukan pengalaman, apakah kekerapan mengaplikasikan kaedah memperbaiki pengaratan tetulang konkrit yang berikut /
Based on experience, what is the frequency of applying the following corrosion repair methods for steel reinforced concrete?

**	1	2	3	4	5
(a) Patch repair method	☐	☐	☐	☐	☐
(b) Perlindungan katodik / *Cathodic protection*	☐	☐	☐	☐	☐
(c) Pengelakan katodik / *Cathodic prevention*	☐	☐	☐	☐	☐
(d) Pengeluaran klorida / *Chloride removal*	☐	☐	☐	☐	☐
(e) Pengalkalian semula / *Realkalization*	☐	☐	☐	☐	☐

13. Berpandukan pengalaman, berapa kerapkah kegagalan struktur disebabkan oleh pengaratan besi tetulang /
Based on experience, what is the frequency of a structure failure caused by corrosion of steel reinforcement?

**	1	2	3	4	5
	☐	☐	☐	☐	☐

14. Berdasarkan pengalaman, apakah masalah-masalah yang utama yang sering dihadapi dari segi aspek pengaratan besi tetulang ? Sila susun mengikut tahap kepentingan masing-masing. /
Based on experience, what are the main issues that are frequently encountered? Please rank.

1 = Sangat utama / Very utmost ⟶ N = Kurang utama / Less utmost

☐ Tetulang yang dihantar ke tapak sudahpun karat /
Rebars were already corroded before reaching to site.

☐ Tiada tempat yang sesuai untuk menyimpan tetulang /
Lack of proper storage area for rebars

☐ Kurang pengetahuan untuk mengendalikan pengaratan tetulang /
Lack of knowledge on proper handling of corroded rebar.

☐ Penggunaan gred konkrit yang rendah /
Application of lower grade concrete

☐ Aspek rekabentuk penutup konkrit / *Insufficient design of concrete cover*

☐ Kurang pengawasian ke atas kualiti kerja /
Lack of supervision on the quality of work

☐ Kesan alam sekeliling / *Environmental effect*

☐ Kekurangan sumber wang untuk mengaplikasikan kaedah pengelakan pengaratan besi tetulang /
Lack of fund to conduct proper application of corrosion prevention method on the rebar.

Lain-lain / *Others*:

☐ ______________________________
____

☐ ______________________________
____

☐ ______________________________
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15. Apakah cadangan anda dalam mengurangkan masalah pengaratan besi tetulang ? /
What are your suggestions on how to reduce the problem of corrosion of steel reinforcement?

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Kerjasama anda amatlah dihargai. Terima Kasih !
Your cooperation is very much appreciated, Thank you !